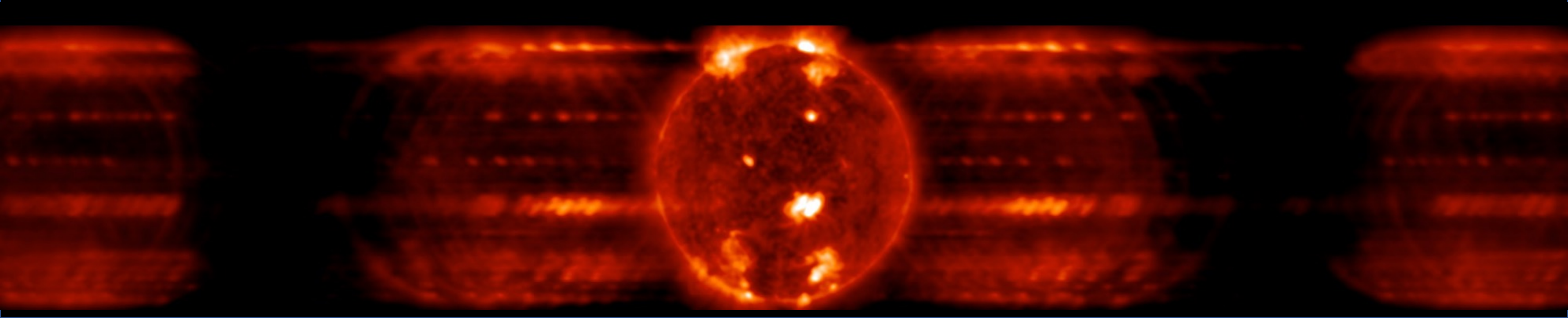
Probing the Sun with Imaging Spectrographs

Dr. Amy Winebarger, NASA MSFC



Career Path

Undergrad

KING COLLEGE

91-95

Graduate

UAH THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

95-99

Postdocs

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

00-02

NAVAL RESEARCH LABORATORY WASHINGTON, DC

02-05

Professor

06-10

Rocket Scientist

~~Astrophysicist~~

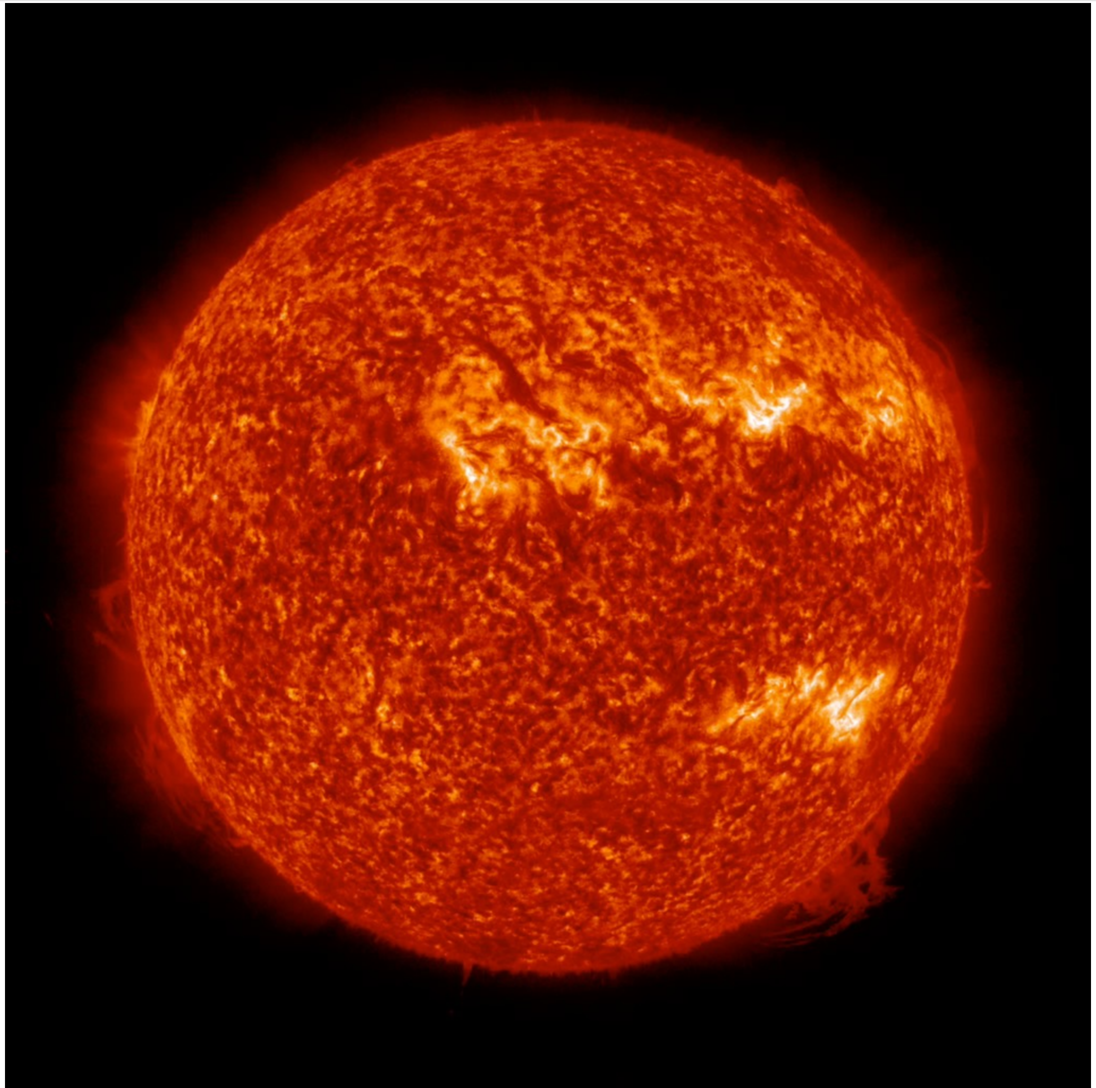
NASA

10-Life

The problem

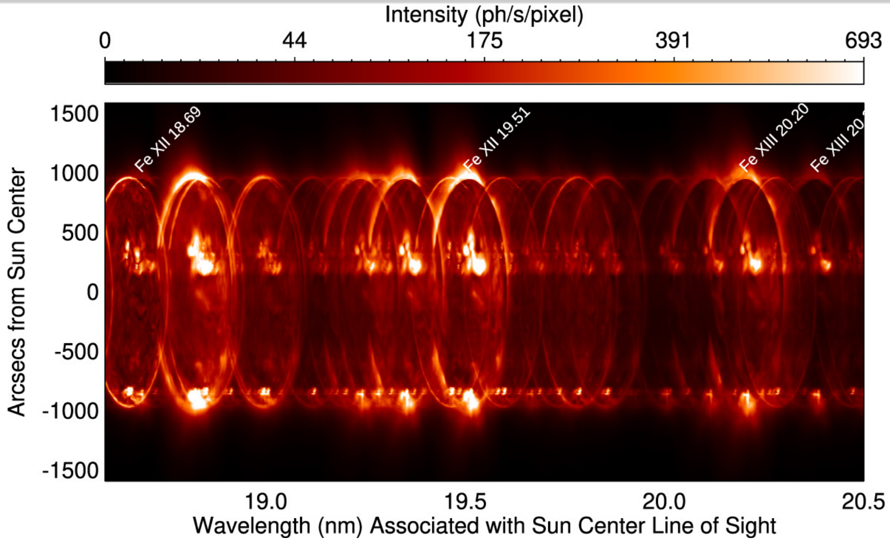
The solar atmosphere is

- ***multi-dimensional***
- ***complicated***
- ***unpredictable***



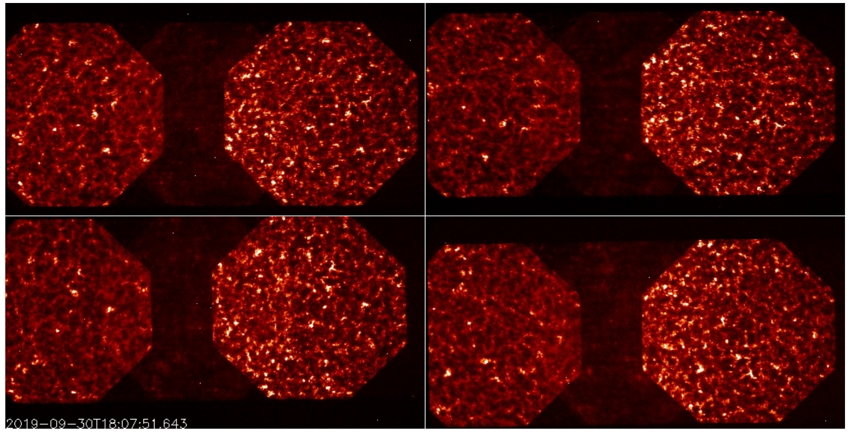
Solar observations are inherently limited.

The goal of today's talk

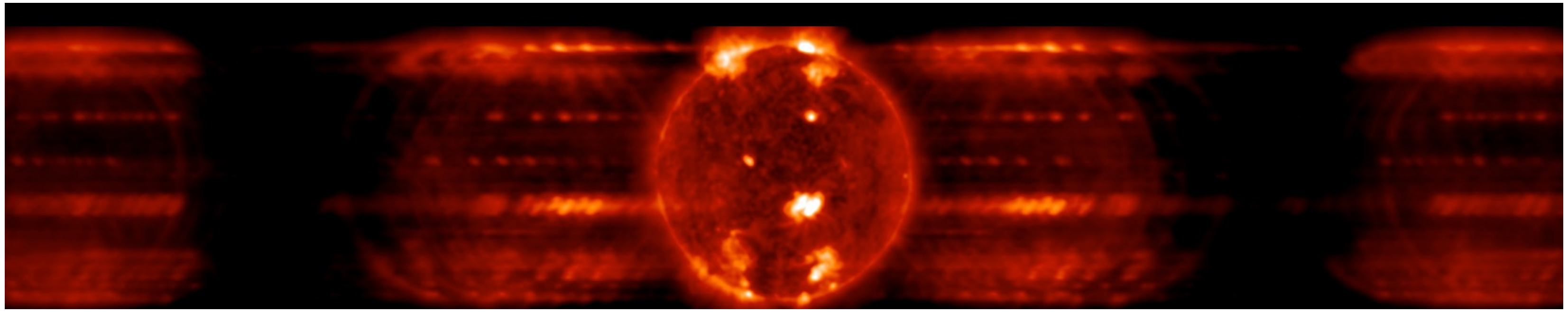


Expected COSIE-S data

Imaging Spectrographs provide useful and powerful data.



Observed ESIS data



Expected MOXSI data

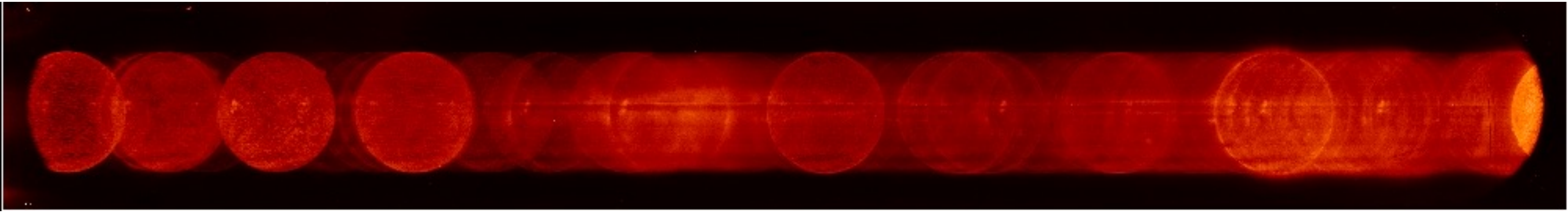
What is an Imaging Spectrograph?

An Imaging Spectrograph is instrument

- *with a grating*
- *with spatial resolution*

The Imaging Spectrographs in this talk are also slitless:

- *with large field of view*



Spectroheliograms or “Overlappograms” - spatial and spectral data are overlapped.

Outline

- Why do we need imaging spectrographs?
- Didn’t we used to take this data?
  - A nod to the history of this type of instrument
- Recent results from imaging spectrographs

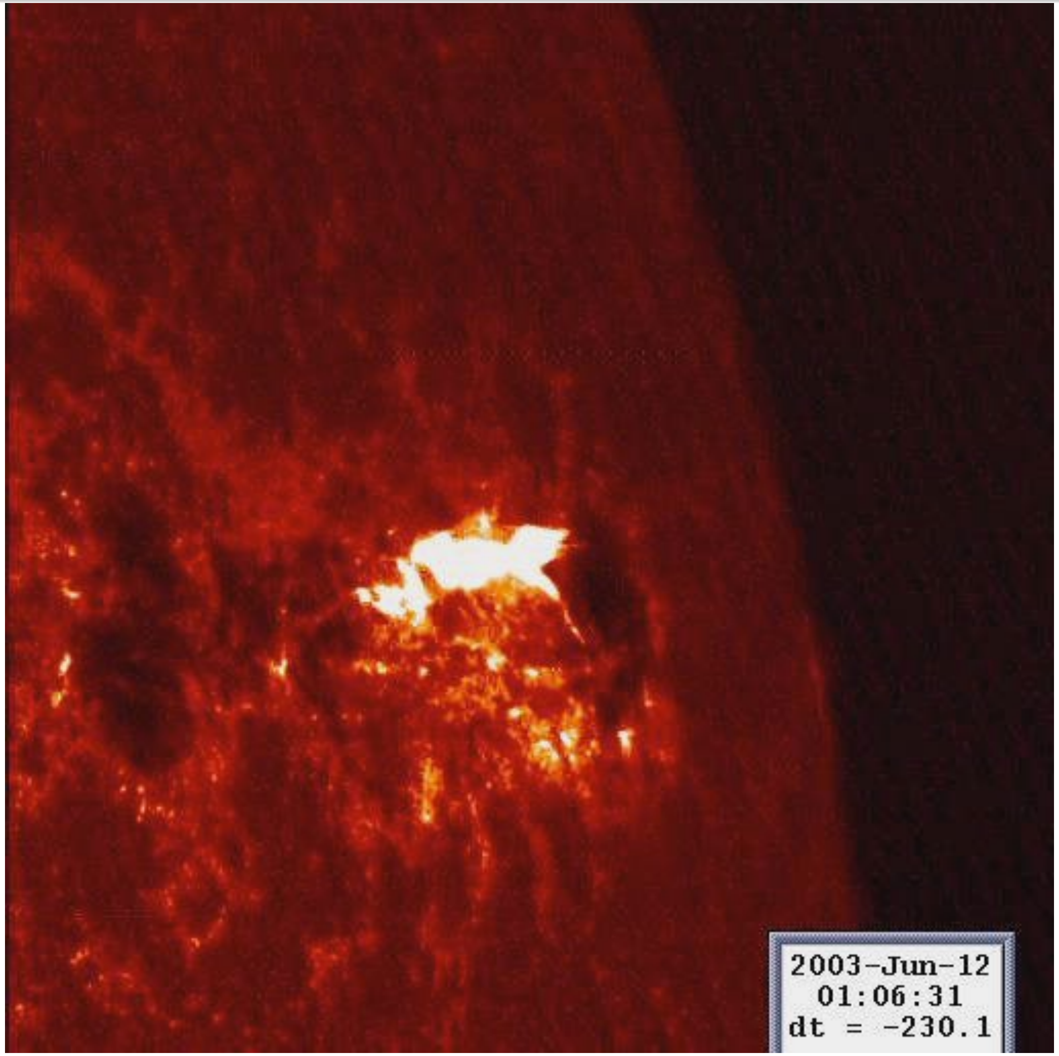
How much energy is released in magnetic reconnection events?

Magnetic reconnection = energy release

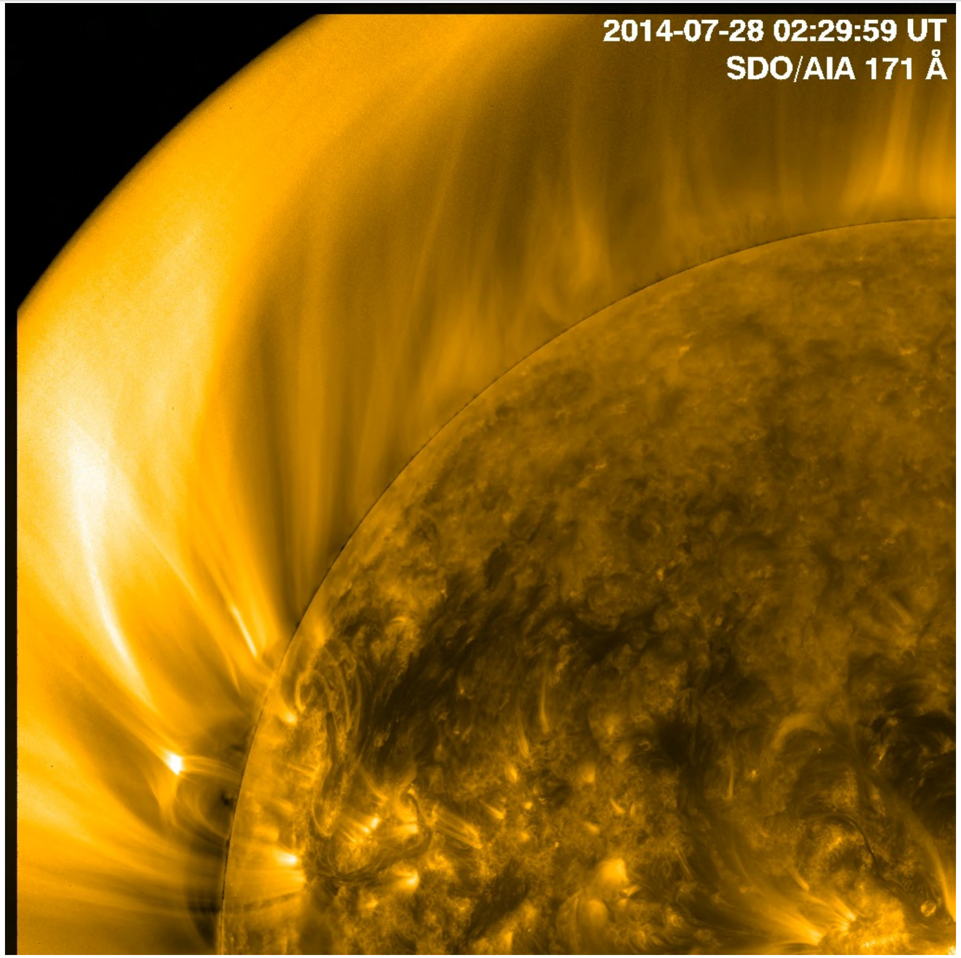
Energy release results in :

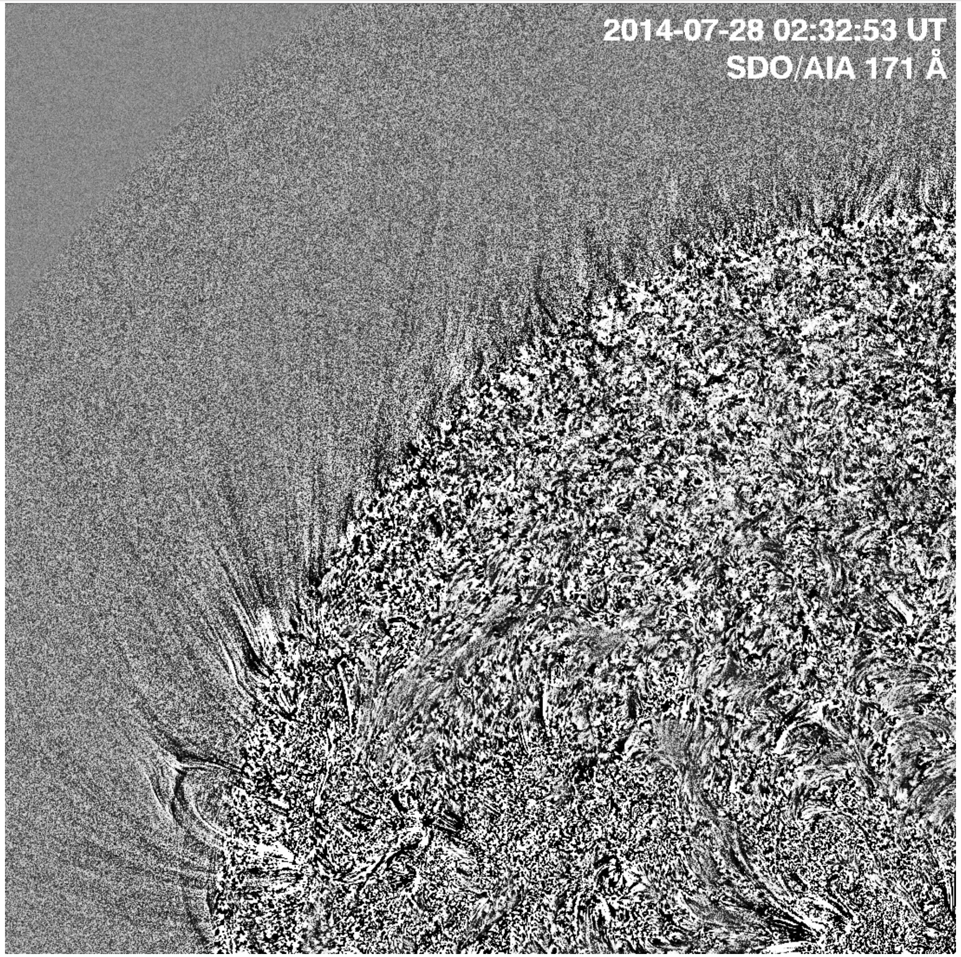
- Increased temperatures
- Increased radiation
- *Extreme velocities*

Measuring velocity requires spectroscopy.



How do space weather events evolve?





Evolution of CMES depends on

- temperature and
- *density* structure

Measuring density requires spectroscopy.

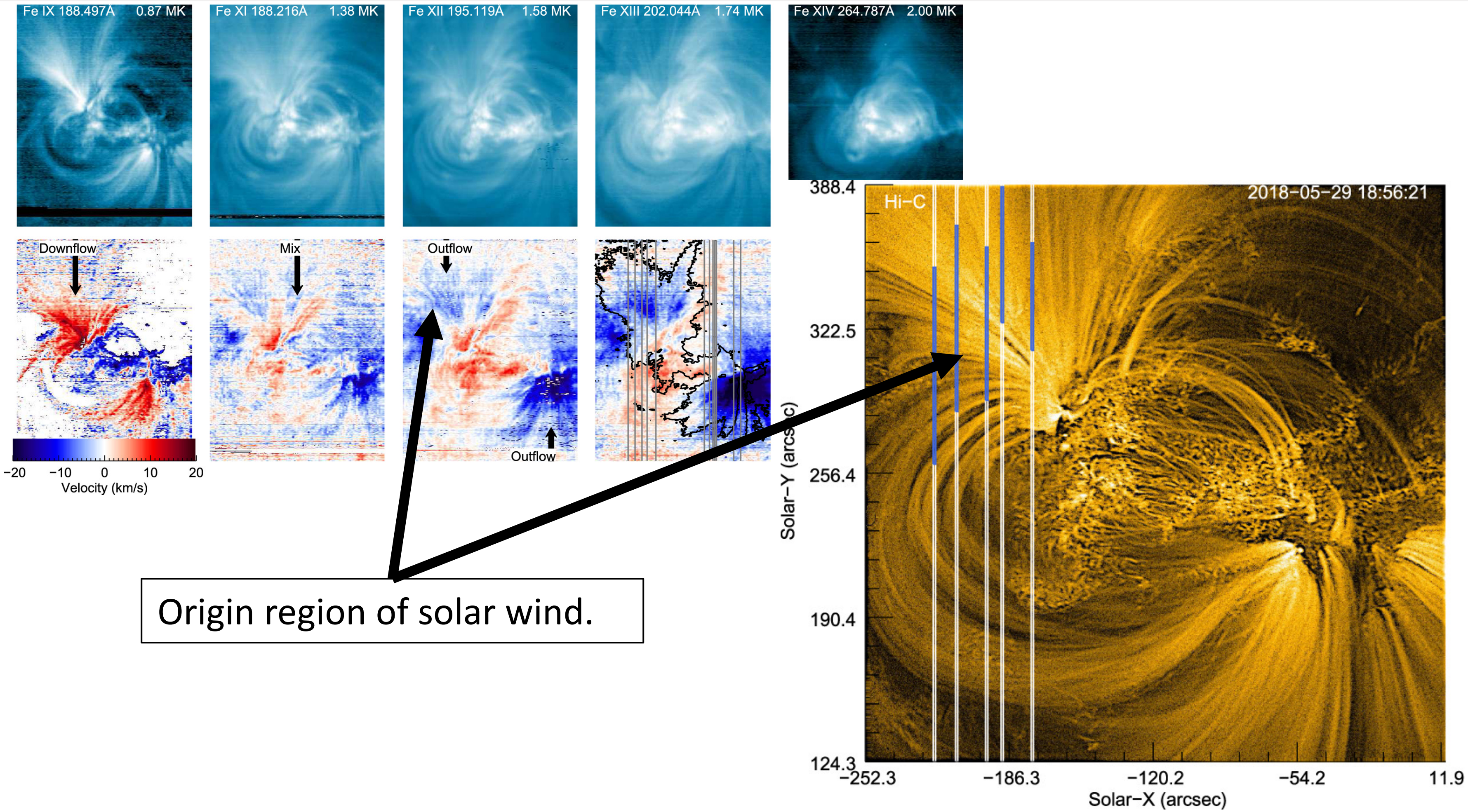
Movies courtesy of Leon Golub (SAO)

What fundamental processes drive coronal heating and the slow solar wind?

Abundances constrain:

- coronal heating mechanism
- origin of the solar wind.

Measuring abundances requires spectroscopy.

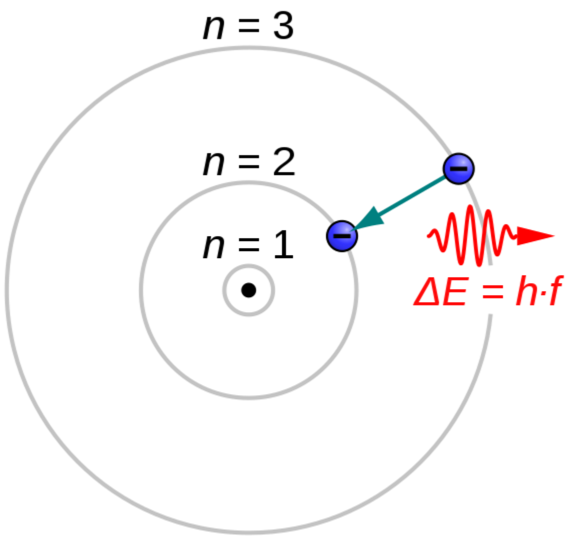


Brooks, D., et al. 2020 ApJ, 894, 144

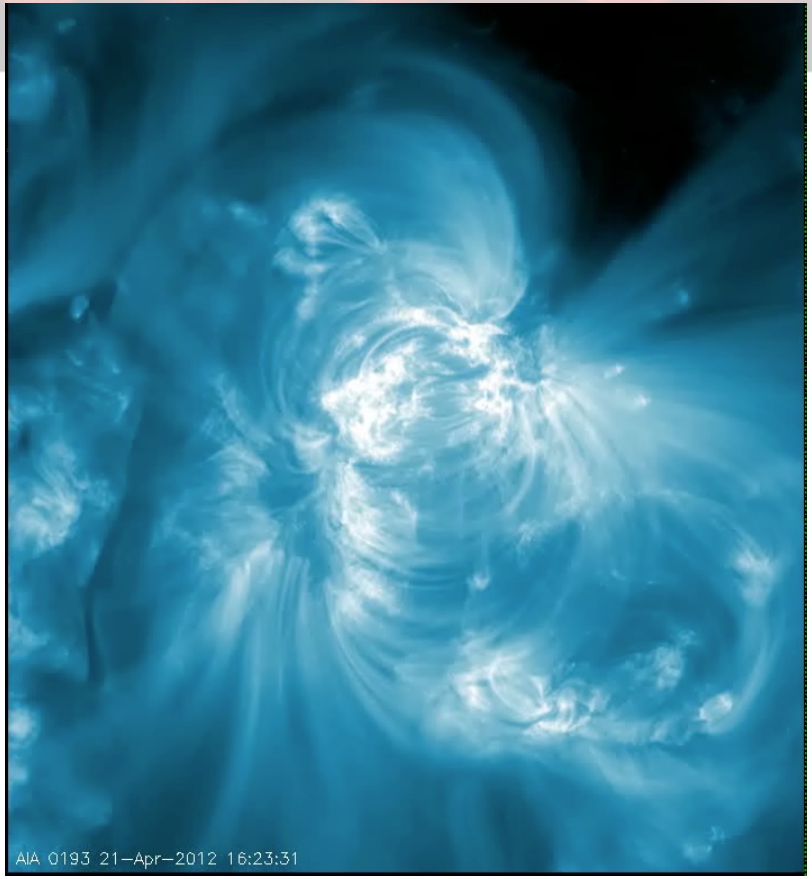
Holy grail data set

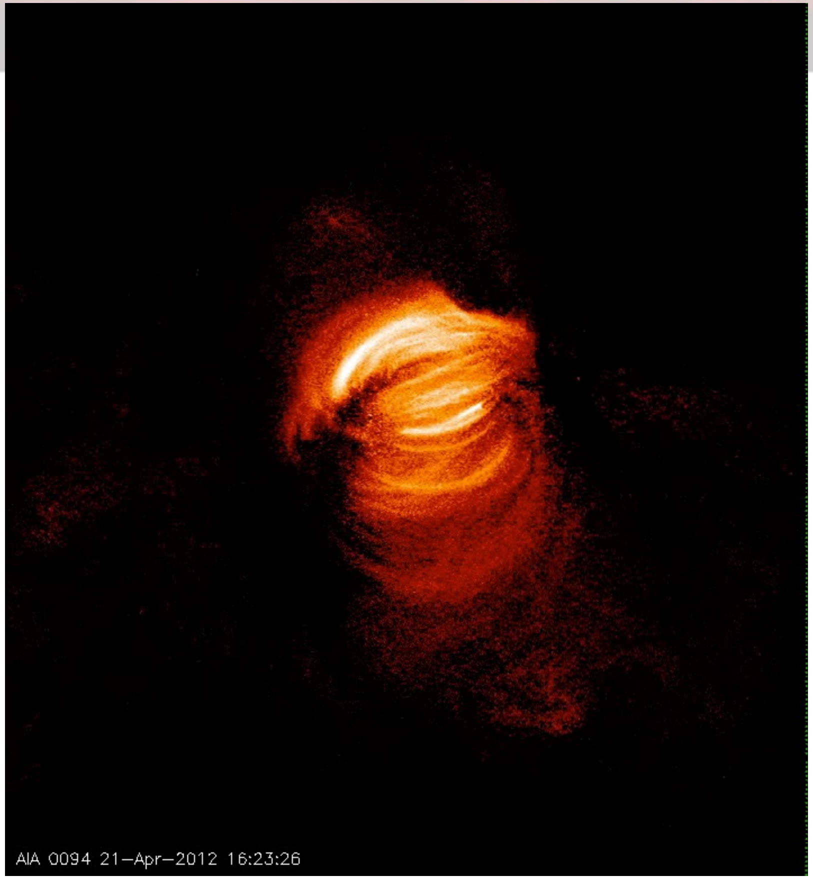
- Temperature
- Density
- Abundance
- Velocity

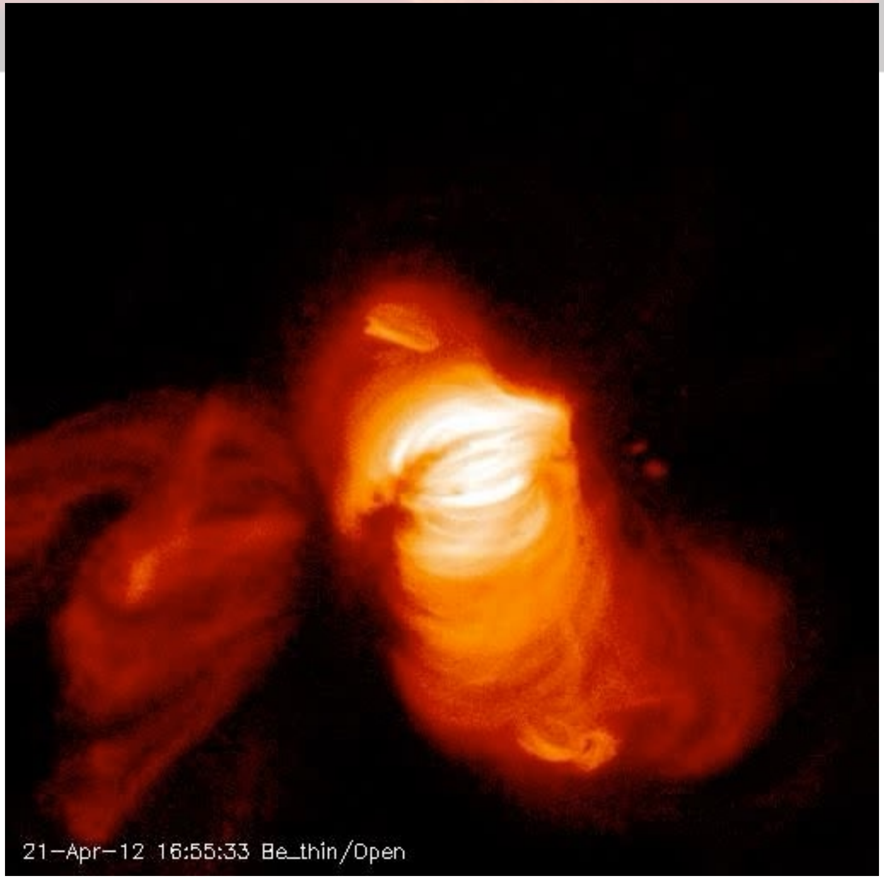
As a function of space and time



Temperature diagnostics



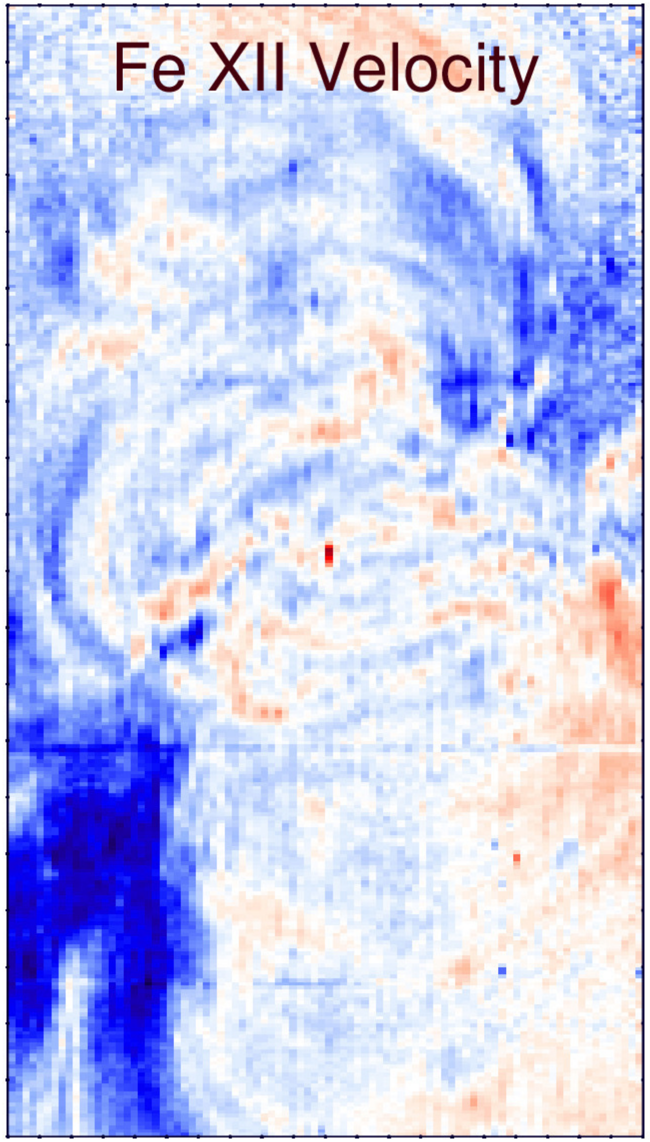


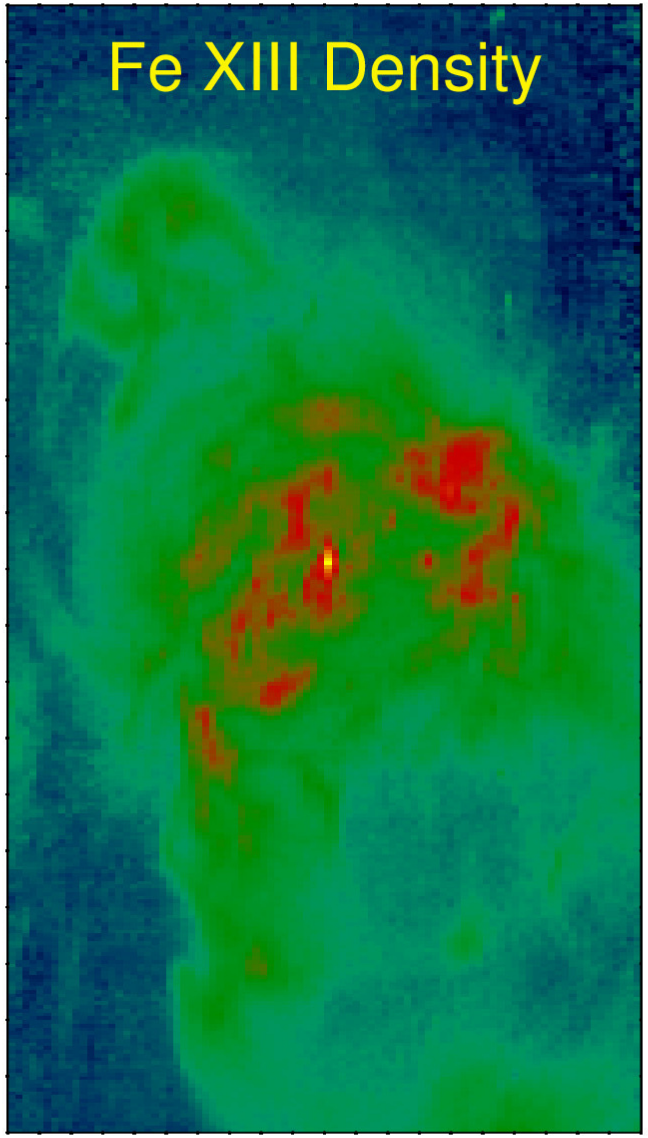


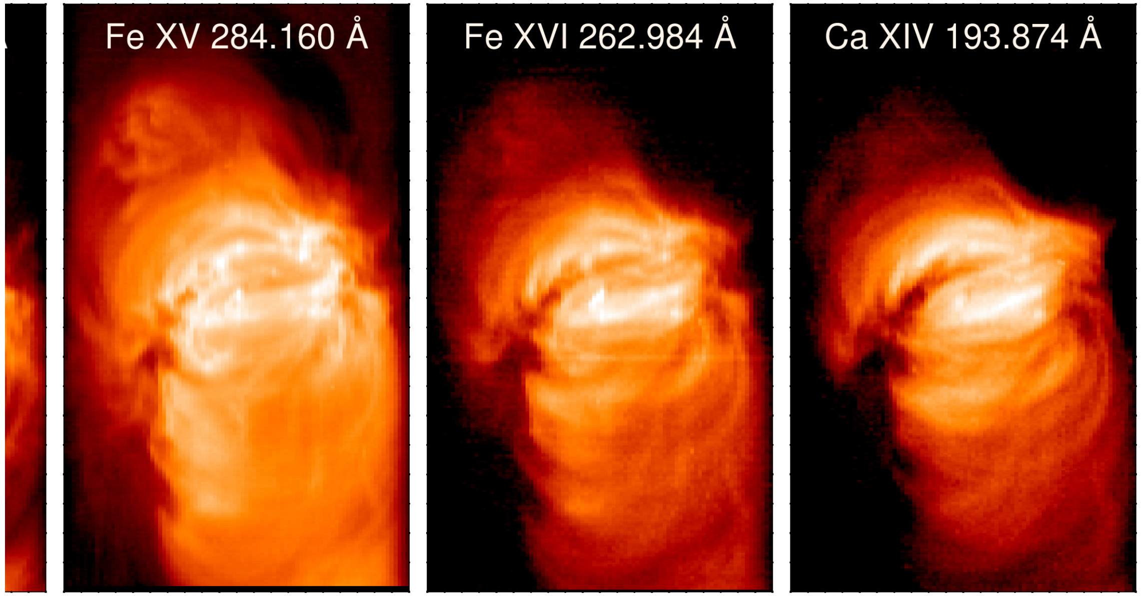
Narrowband EUV images from AIA and soft x-ray filtergram images from XRT provide temperature discrimination.

Movies and images courtesy of Harry Warren (NRL)

Holy grail data set



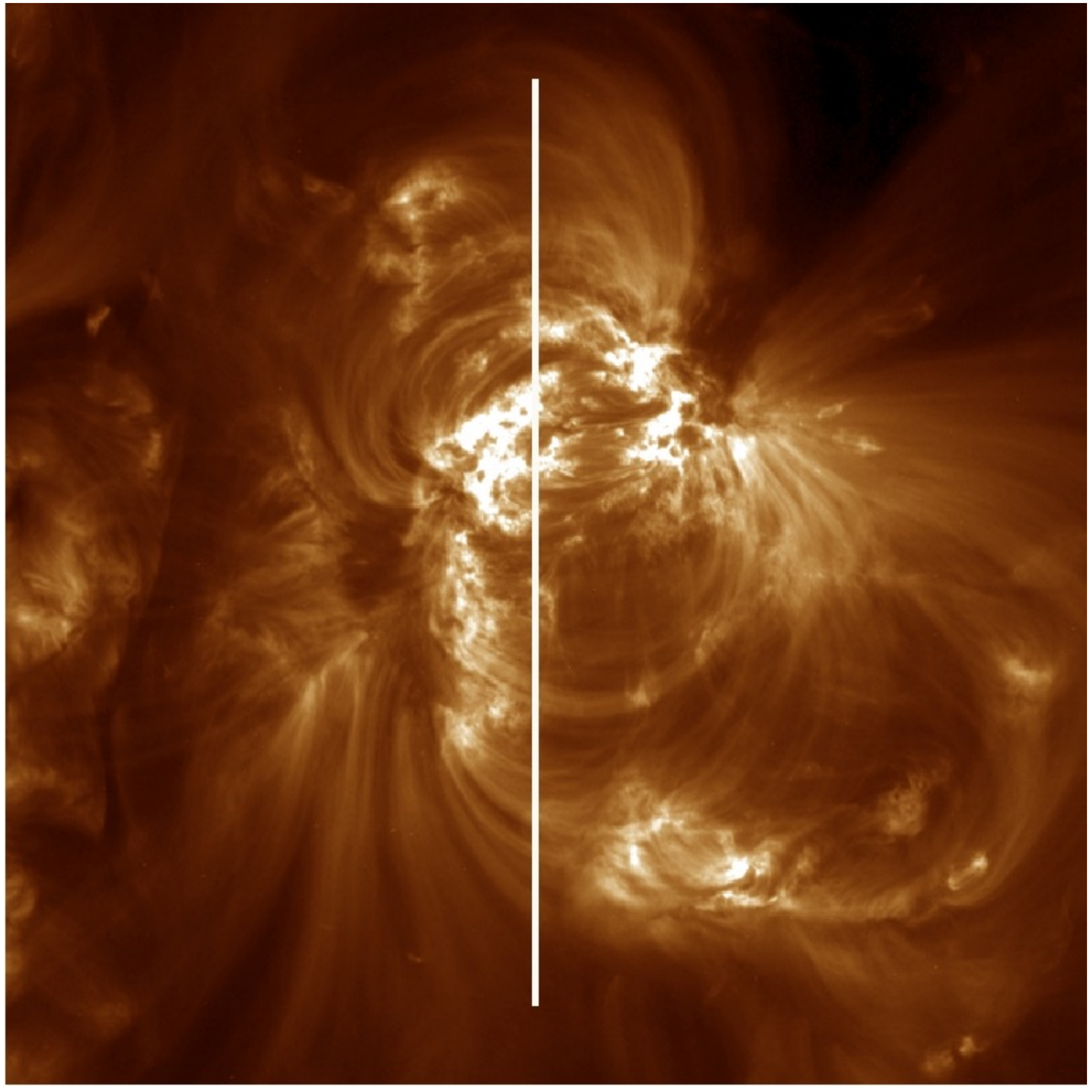


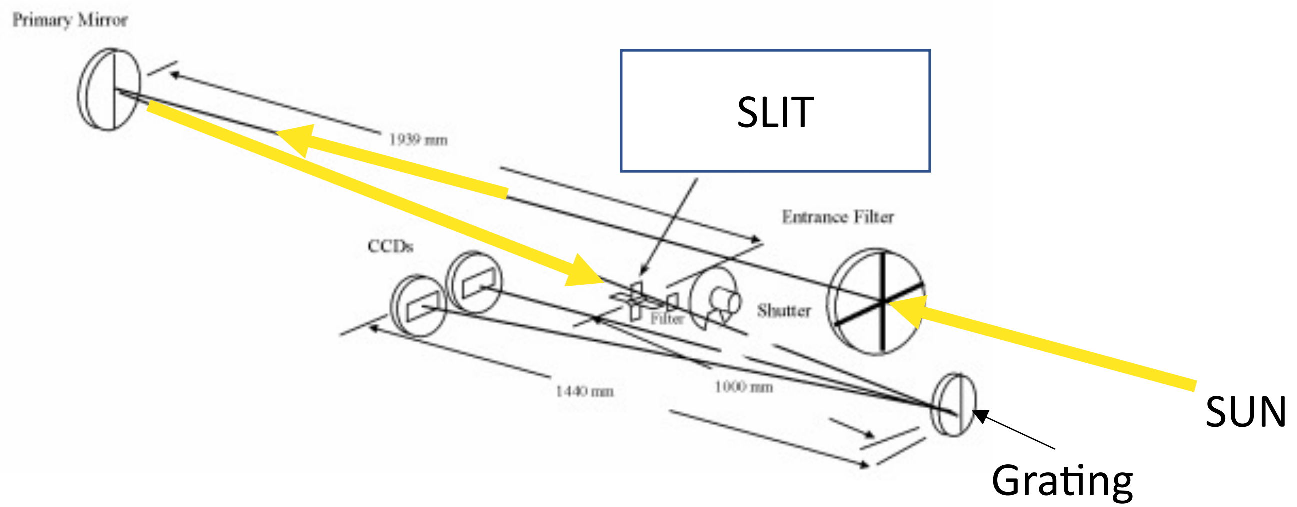


For additional diagnostics, spectroscopy is required.

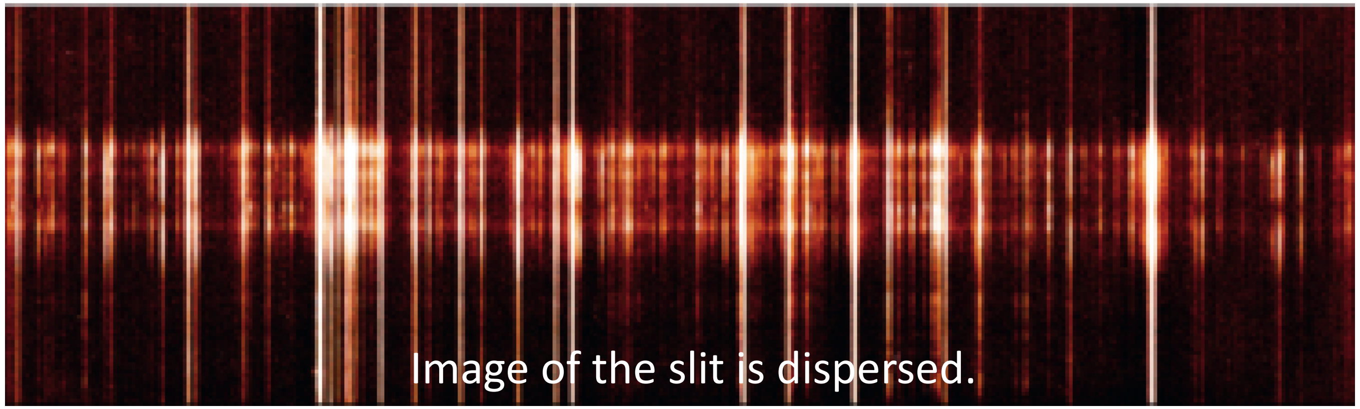
Movies and images courtesy of Harry Warren (NRL)

Example: EUV Imaging Spectrometer (EIS)

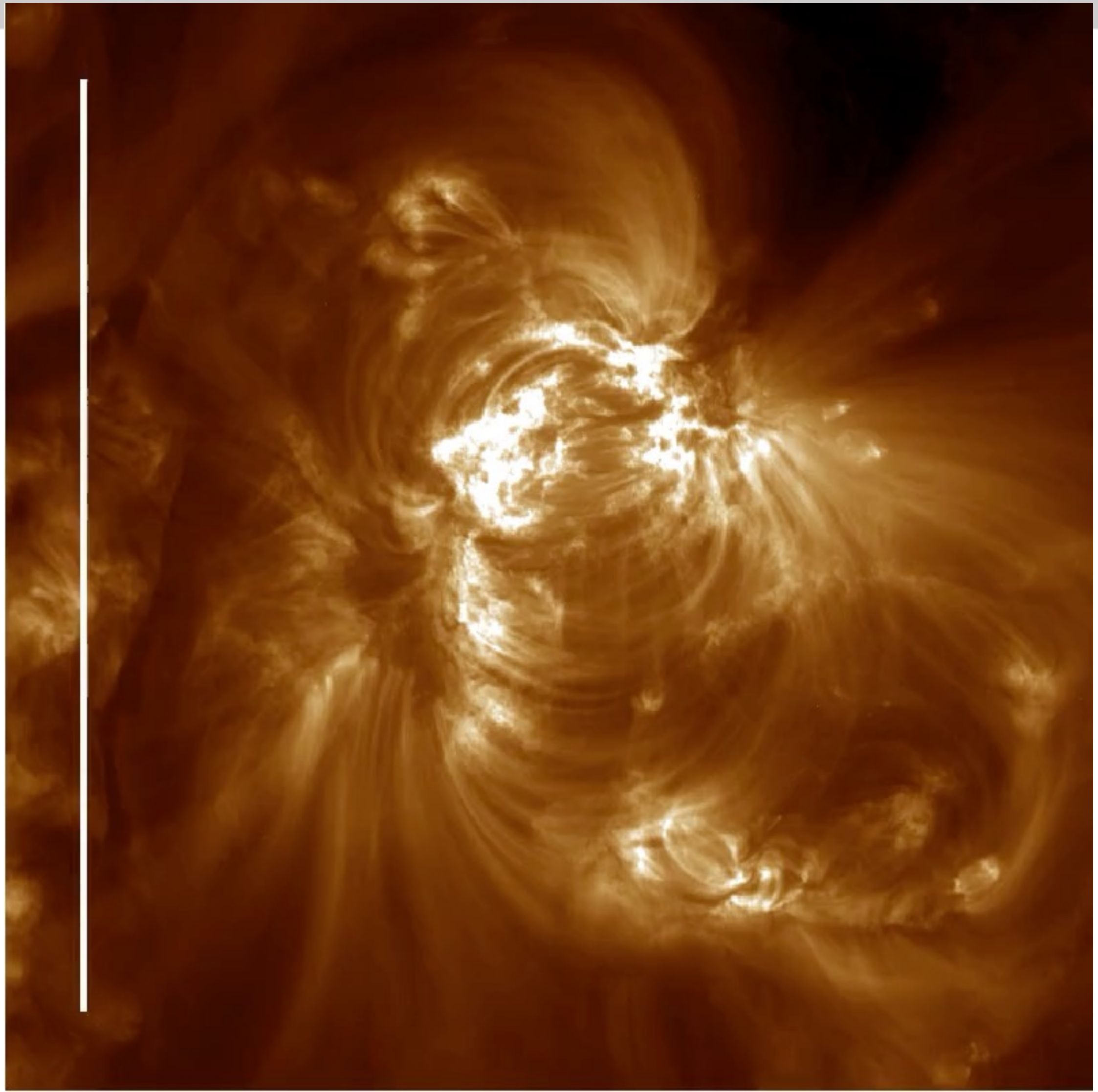




Culhane, APS Conf Series, 2007



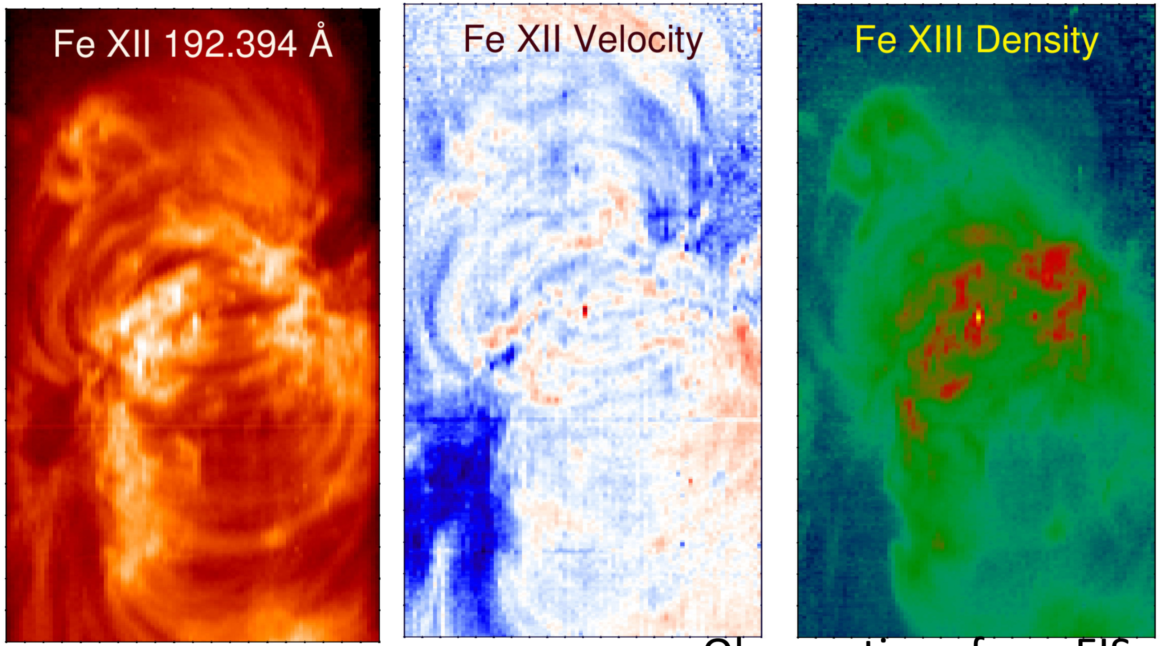
Holy grail data set



Single-slit spectrograph

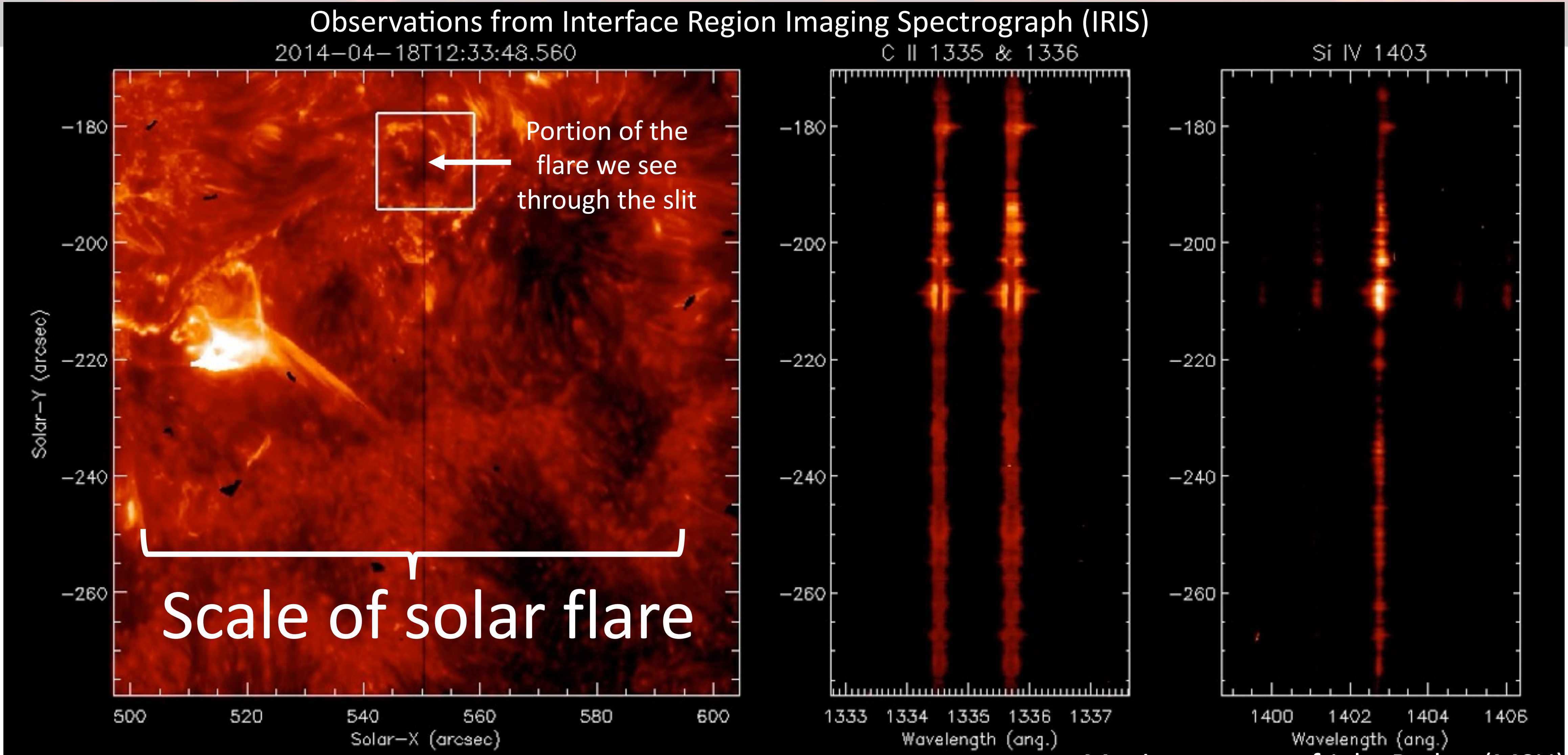
- At the expense of temporal resolution

Examples: EIS, IRIS



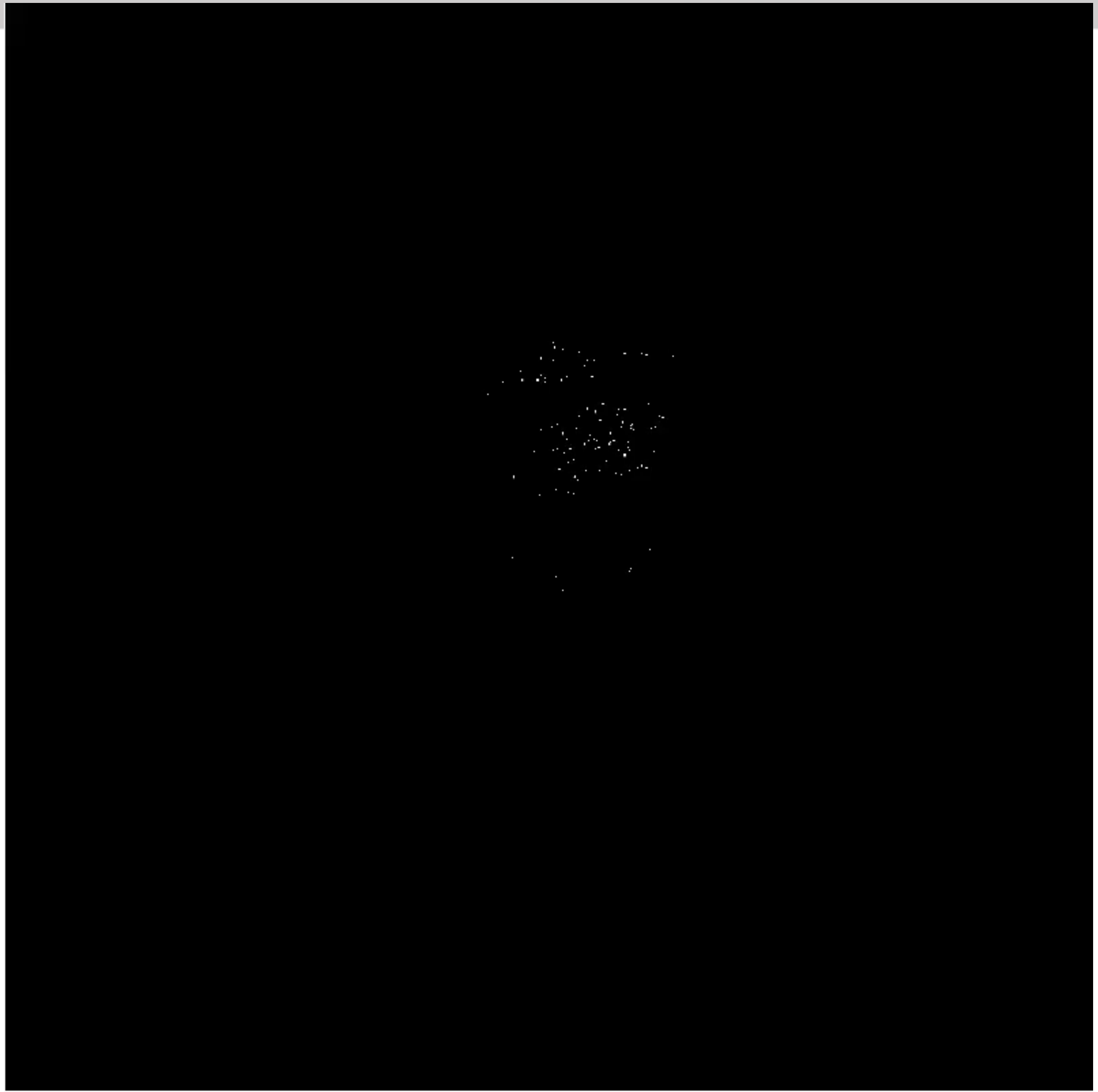
Observations from EIS

In large scale eruptions, the problem is even worse



Movie courtesy of Jake Parker (MSU)

Holy grail data set



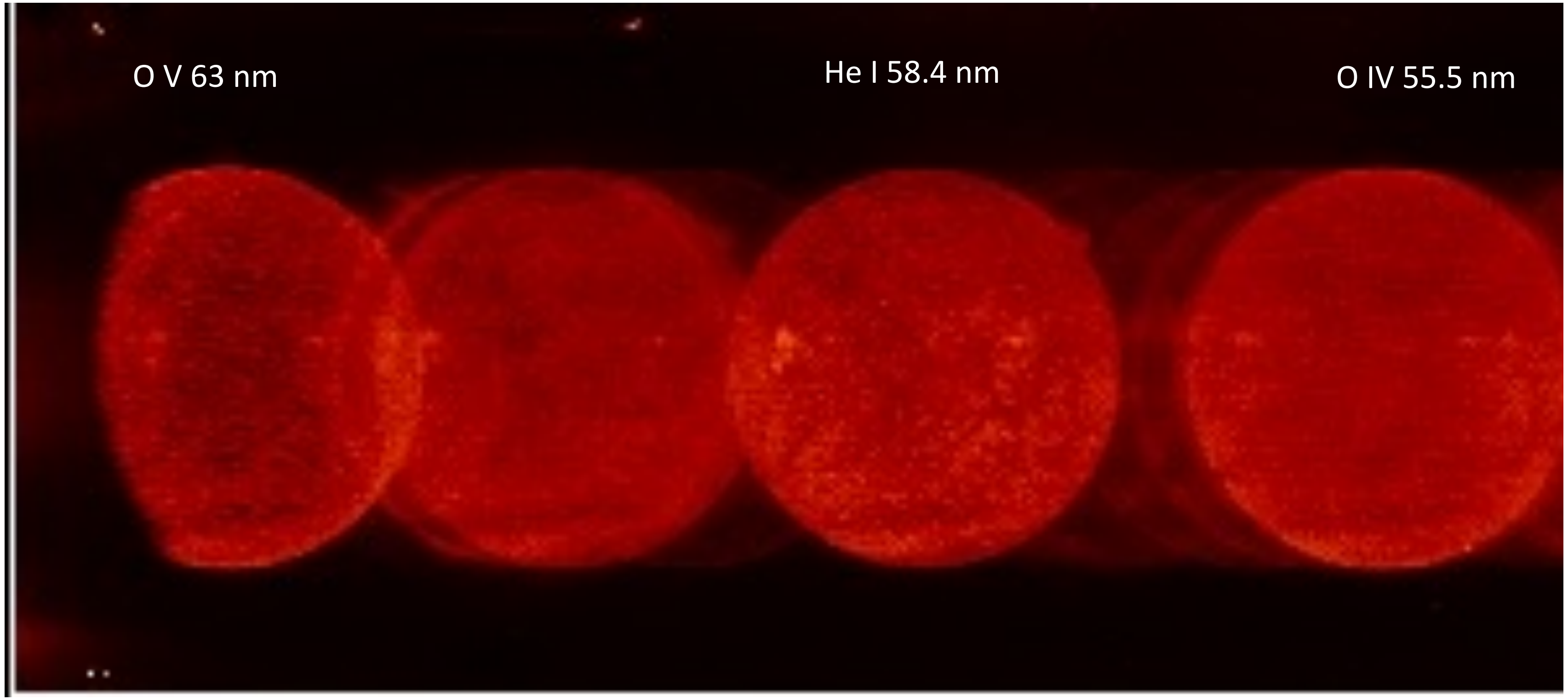
Photon counting devices

- At the expense of energy range and resolution
- Only works for energy > 1 kev and has poor spectral resolution

Examples:

- Microcalorimeters
- CMOS devices
- PhoENIX (Japanese instrument)

Holy grail data set



(Slitless) Imaging Spectrograph

- Can acquire large FOV at rapid cadence
- At the expense of spatial/spectral confusion

Examples: ESIS, COSIE, MOXSI, COOL-AID

Outline

✓Why do we need imaging spectrographs?

- Didn’t we used to take this data?
  - A nod to the history of this type of instrument
- Recent results from imaging spectrographs

History

FIG. 8.—Professor Theodore Lyman operating the McCloud gauge connected to his vacuum spectrograph, a photograph made in the Lyman Laboratory of Physics, Harvard University, by Paul Donaldson in the late 1930's.

Prof. Theodore Lyman

THE ASTROPHYSICAL JOURNAL

VOLUME 149 AUGUST 1967 NUMBER 2, PART 1

SOME RESULTS OF TWENTY YEARS OF EXTREME ULTRAVIOLET SOLAR RESEARCH*

RICHARD TOUSEY
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C.

Received November 28, 1966

First flight - June 23, 1946
First measurement - October 10, 1946

History

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SOME RESULTS OF TWENTY YEARS OF EXTREME ULTRAVIOLET SOLAR RESEARCH*

RICHARD TOUSEY
...e Research, Naval Research Laboratory, Washington, D.C.

Received November 28, 1966

First spectroheliogram in Lyman alpha observed on March 13, 1959.

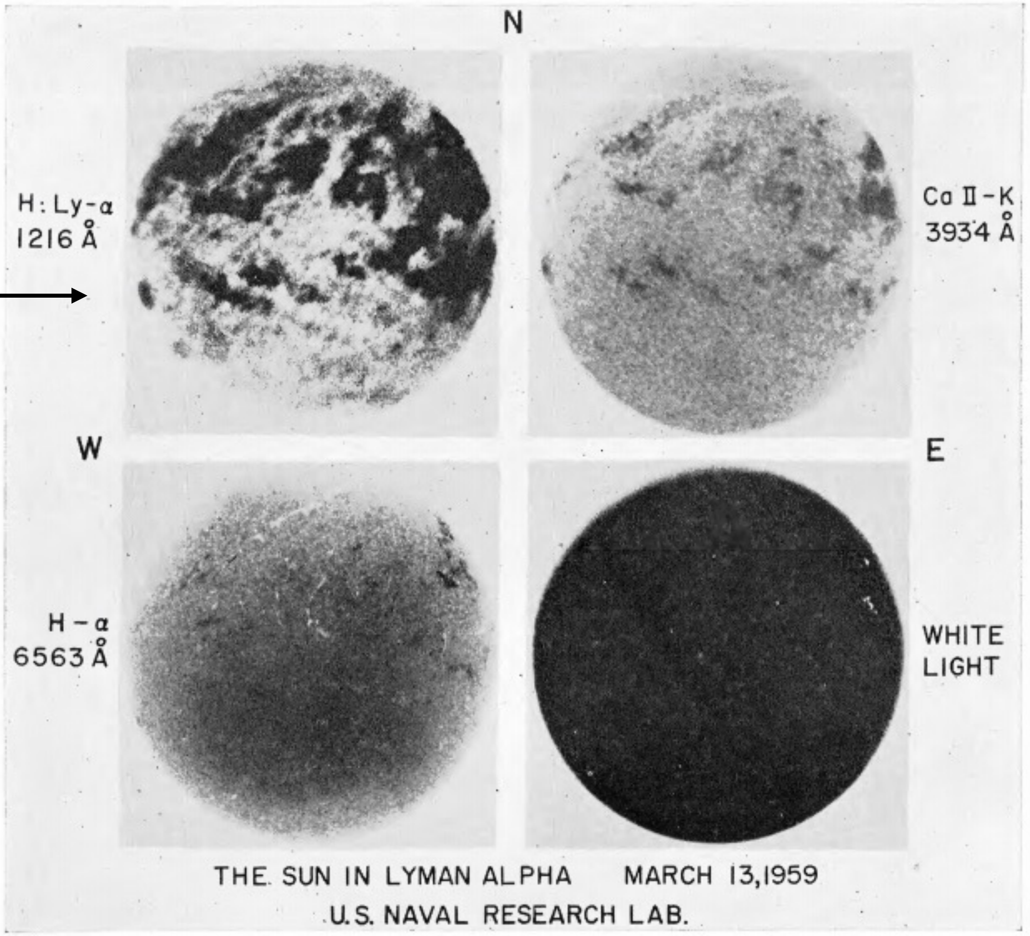

FIG. 24.—The first highly resolved spectroheliogram in hydrogen Lyman-α, obtained by NRL on March 13, 1959, and compared with Ca K, Hα, and white light images from the McMath-Hulbert Observatory, the Naval Research Laboratory, and the Naval Observatory, respectively.

Subsequent rocket flights explored the solar spectrum and revealed the atmospheric structure.

History

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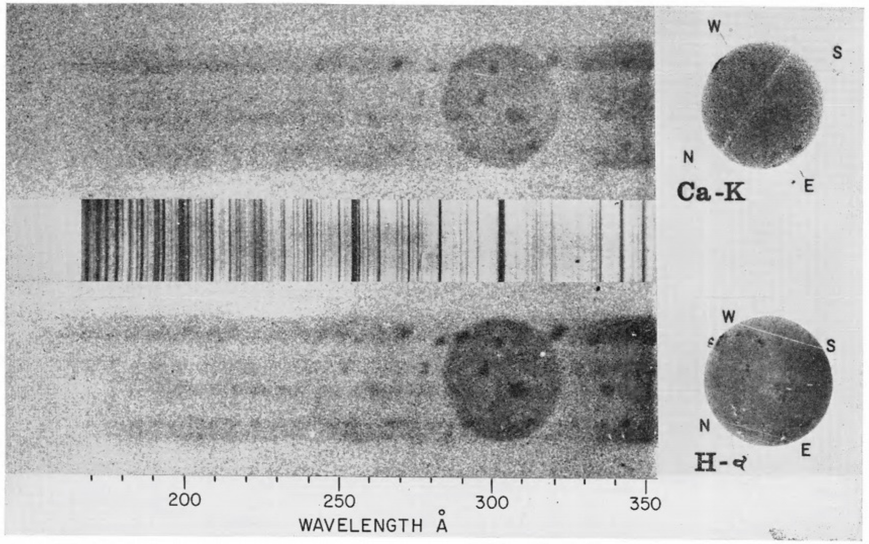


FIG. 25.—The first extreme ultraviolet spectroheliograms made using the aluminum filter technique, compared with a grazing-incidence spectrum. The photographs were obtained by NRL on May 10, 1963.

TOUSEY (*see* page 247)

1963

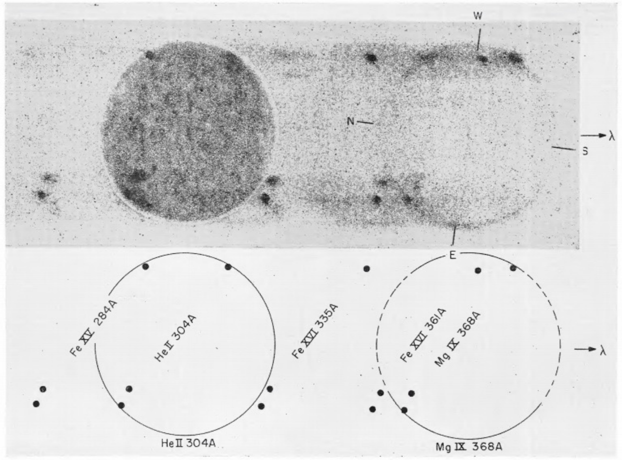


FIG. 26.—Spectroheliograms made by NRL on February 1, 1966, when the Sun was very quiet, showing the greatly different appearance of the disk in He II, Mg IX, and Fe XV and XVI.

TOUSEY (*see* page 248)

1965

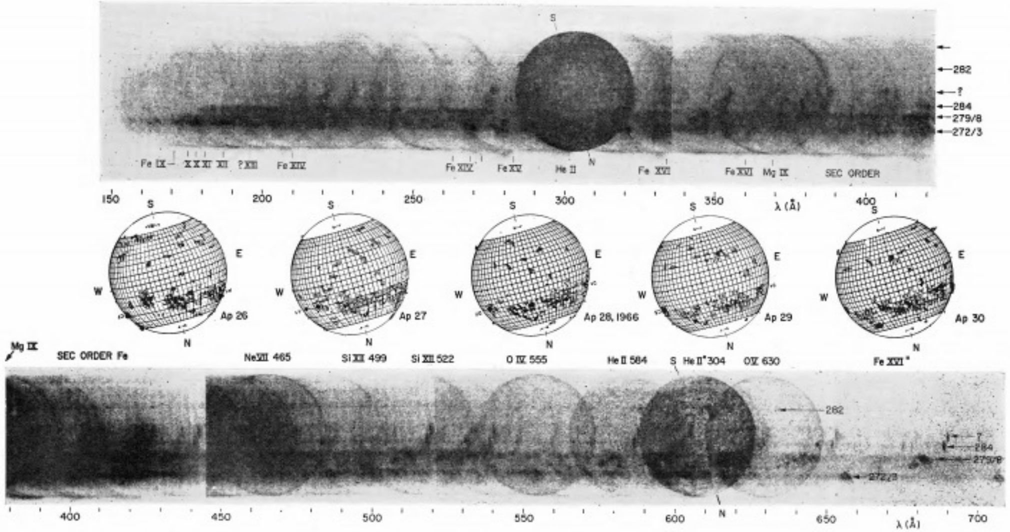


FIG. 27.—The entire range of spectroheliograms photographed by NRL on April 28, 1966, with resolution approaching 10″. Maps from the Fraunhofer Institute, and the McMath plage numbers are shown. The range of intensities was too great to reproduce properly, even though different prints were spliced together.

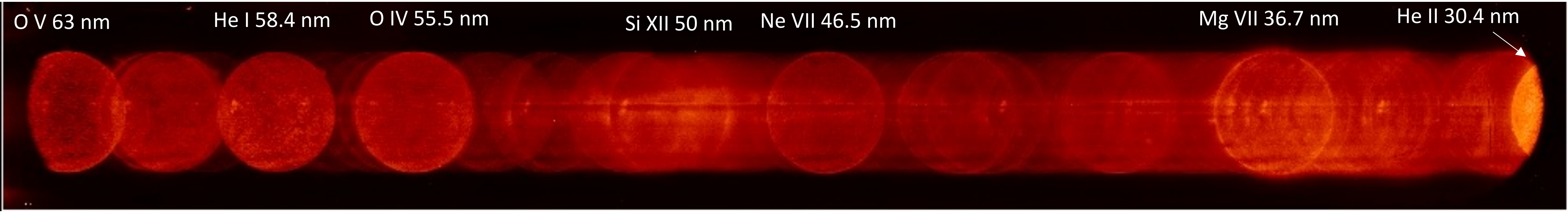
TOUSEY (*see* page 248)

1966

“Therefore this image is not easy to interpret.” - R. Tousey

History

Skylab S082A – long wavelength range



Spectroheliograms were obtained by astronauts from May 14, 1973 – February 8, 1974.

Skylab was the only time spectroheliograms were obtained by NASA on an orbiting satellite.

Skylab data have been digitized and are available: https://lasco-www.nrl.navy.mil/skylab/index.php?p=content/so82a

Outline

- ✓Why do we need imaging spectrographs?
- ✓Didn’t we used to take this data?
  - A nod to the history of this type of instrument
- Recent results from imaging spectrographs

Marshall Grazing Incidence X-ray Spectrometer (MaGIXS)

#Imaging_Spectrograph #Soft_X-ray #Hot_Corona

MaGIXS

NASA MSFC - SAO - MIT - Izentis - UCLan

Amy Winebarger (NASA MSFC) - PI

Sabrina Savage (NASA MSFC) - PS

Ken Kobayashi (NASA MSFC) – IS

P. S. Athiray (UAH)

Dyana Beabout (NASA MSFC)

Stephen Bradshaw (Rice Univ)

Patrick Champey (NASA MSFC)

Peter Cheimets (SAO)

Jonathan Cirtain (BWXT)

Ed DeLuca (SAO)

Giulio Del Zanna (Univ of Cambridge)

Jaroslav Dudik (Astronomical Institute of the CAS)

Leon Golub (SAO)

Helen Mason (Univ of Cambridge)

David McKenzie (NASA MSFC)

Brian Ramsey (NASA MSFC)

Katharine Reeves (SAO)

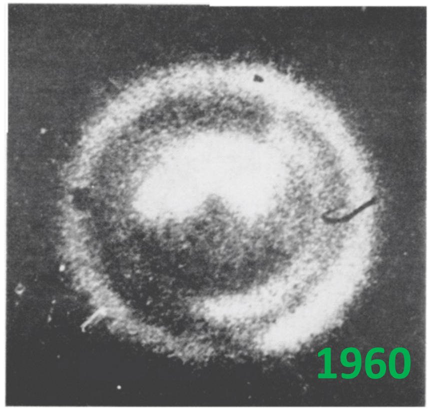
Paola Testa (SAO)

Genevieve Vigil (NASA/MSFC)

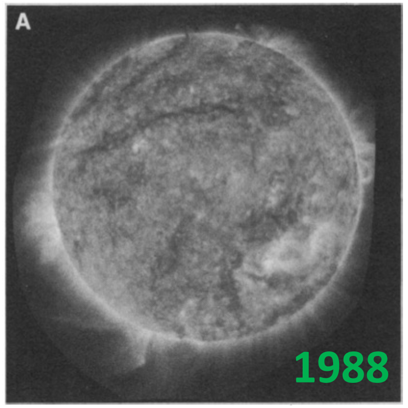
Robert W. Walsh (UCLAN)

Harry Warren (NRL)

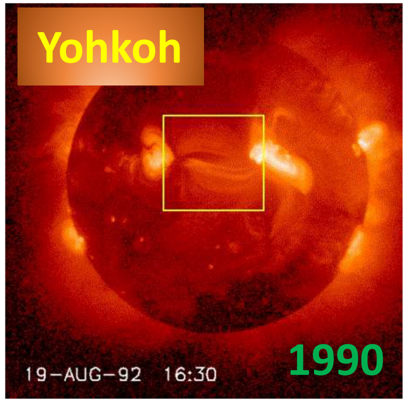
Active region observations

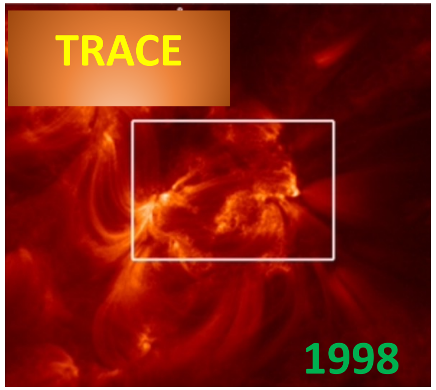


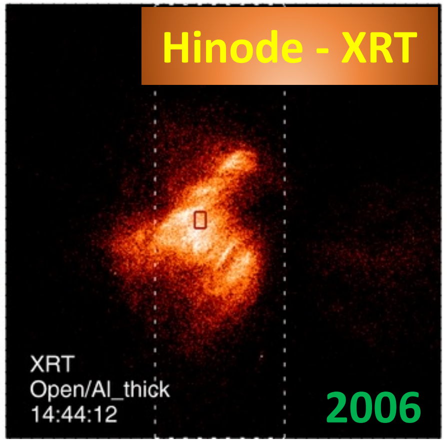
X-ray photograph of the sun, taken from a rocket fired 130 miles above the earth.
SCIENCE, VOL. 131

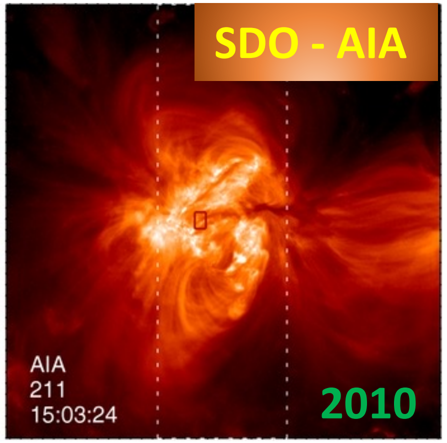


Sounding Rocket Observations









Satellite Observations

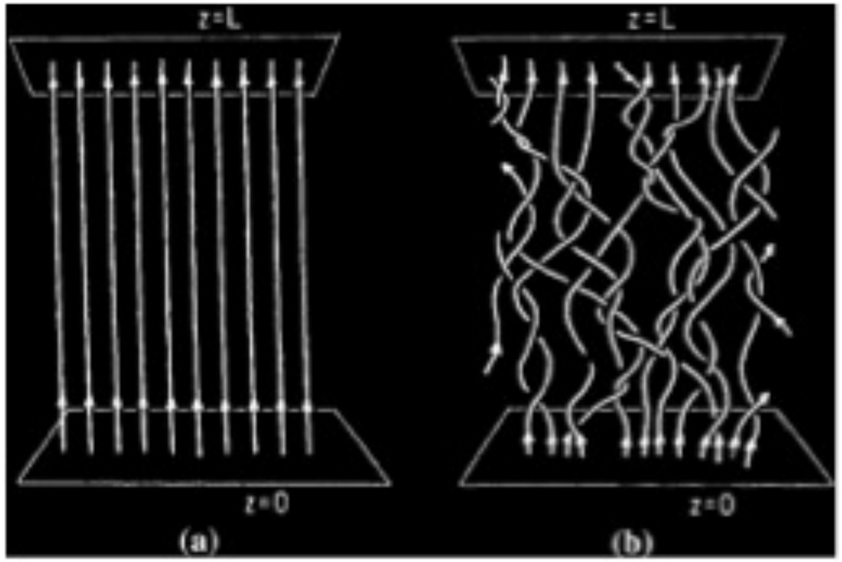
- Early sounding rocket observations discovered presence of 'Hot Corona'

Imaging and spectroscopy via EUV and X-rays

- Exhibit loop structure comprises many strands
- Contains hot loops near core
- Contains relatively cool foot point regions 'Moss'

Competing Theories

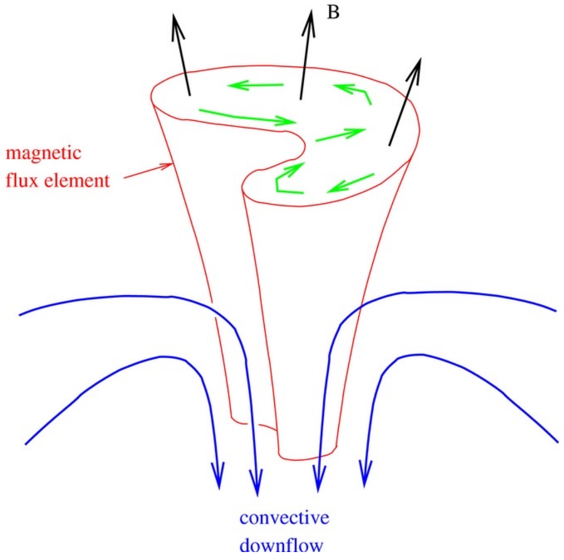
Magnetic Reconnection



$\tau_{heat} >> \tau_{cool}$

Low frequency heating

Wave Dissipation

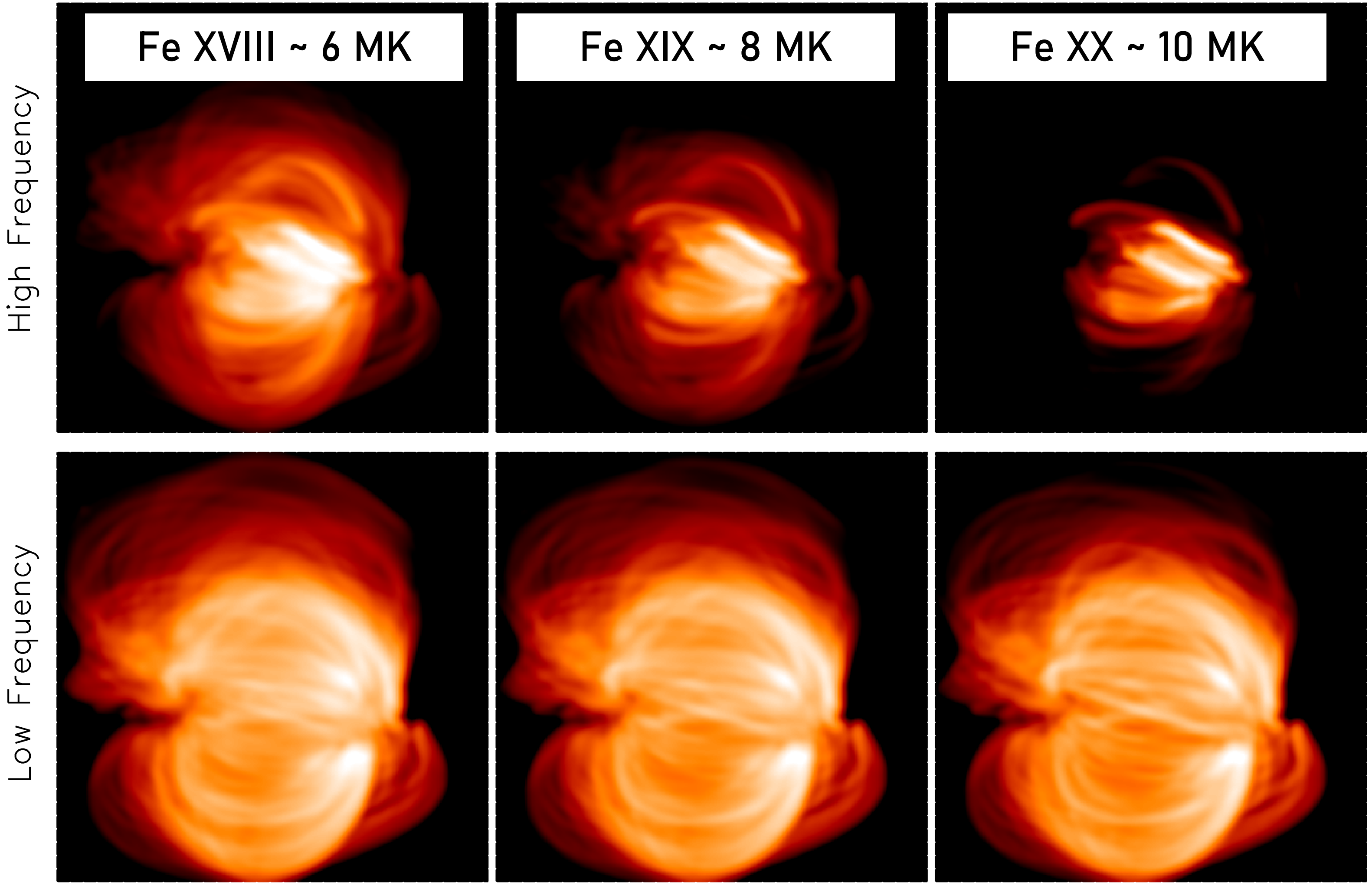


$\tau_{heat} << \tau_{cool}$

High frequency heating

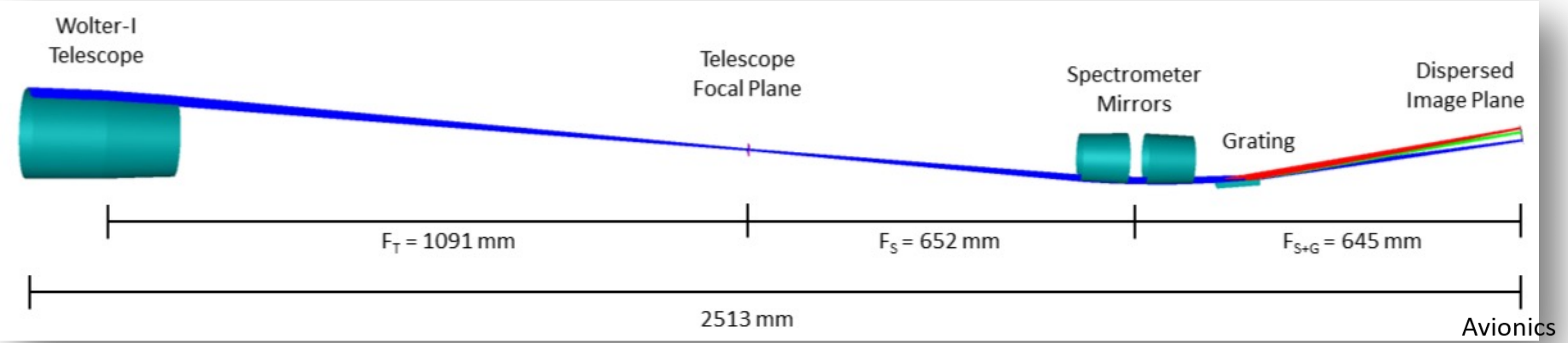
Parker, 1988, ApJ; Van Ballegooijen et al. 2011, ApJ

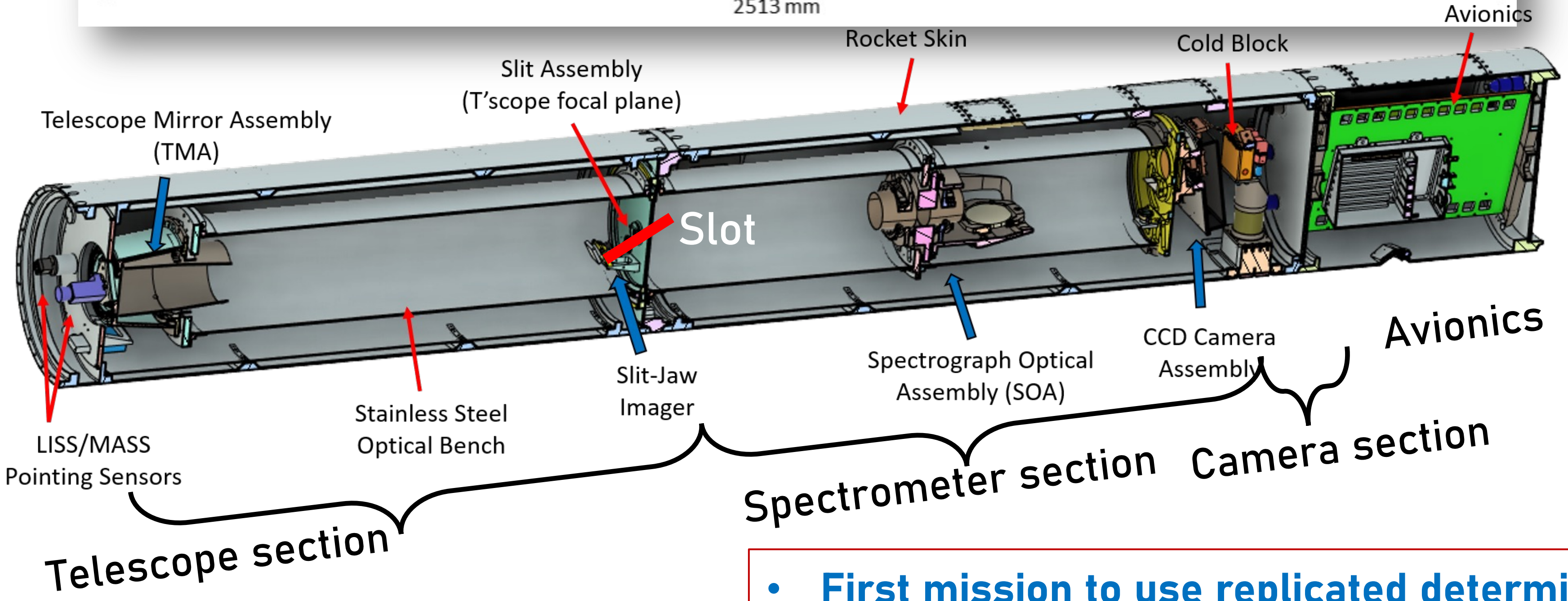
Discriminating Observations



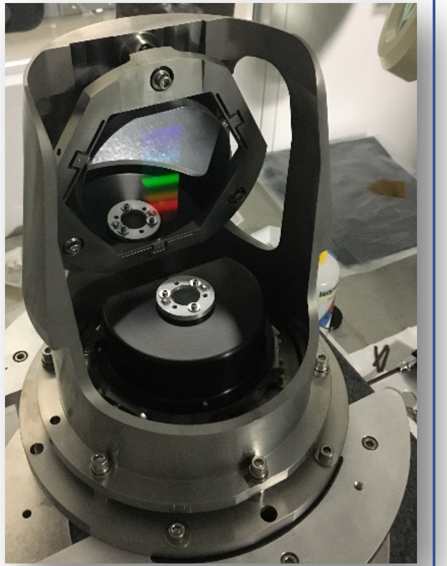
- **High temperature diagnostics– "smoking gun" to detect heating events**

MaGIXS Instrument Design





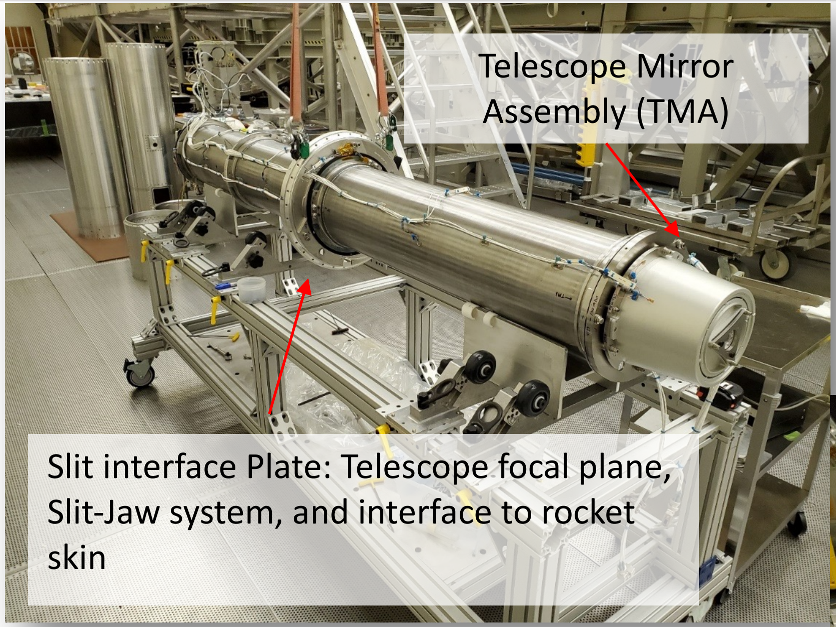
Grating

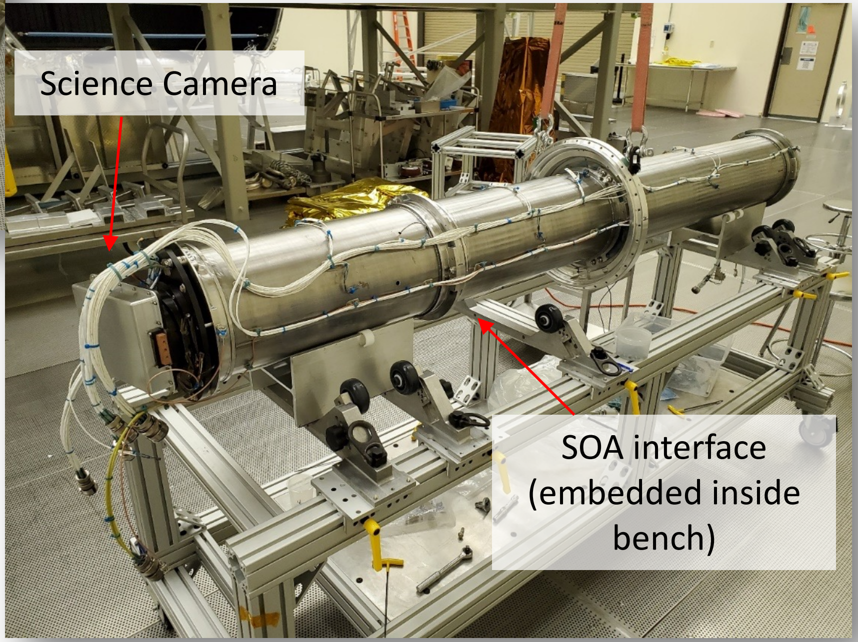


Beam footprint subtends 34°

- **First mission to use replicated deterministic polished X-ray mandrels**

MaGIXS Instrument Alignment and Calibration

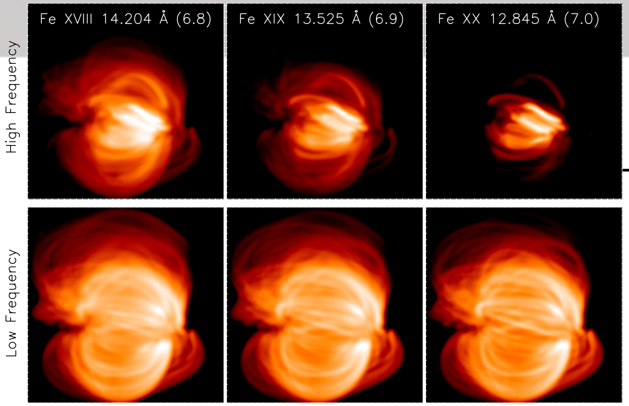




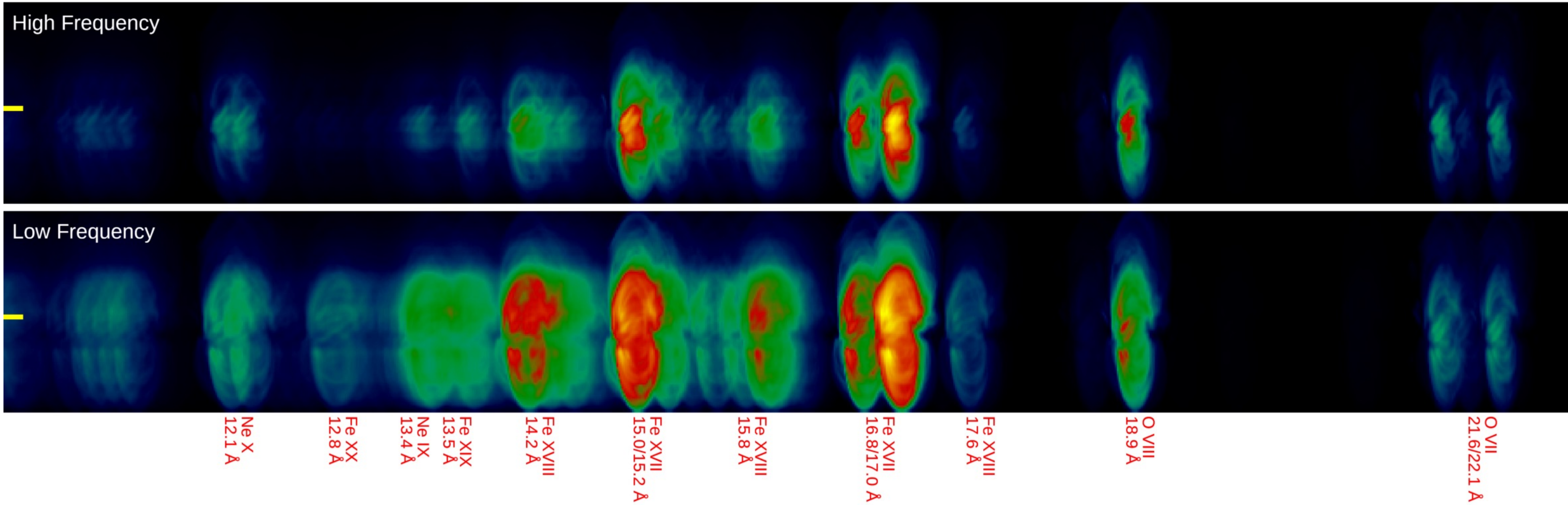
~1.5 m between TMA and SOA

Calibration activities at 500 m X-Ray beamline at MSFC.

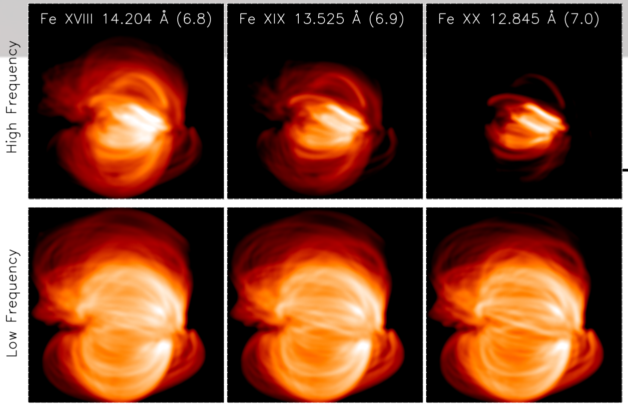
MaGIXS data are “Overlappograms”



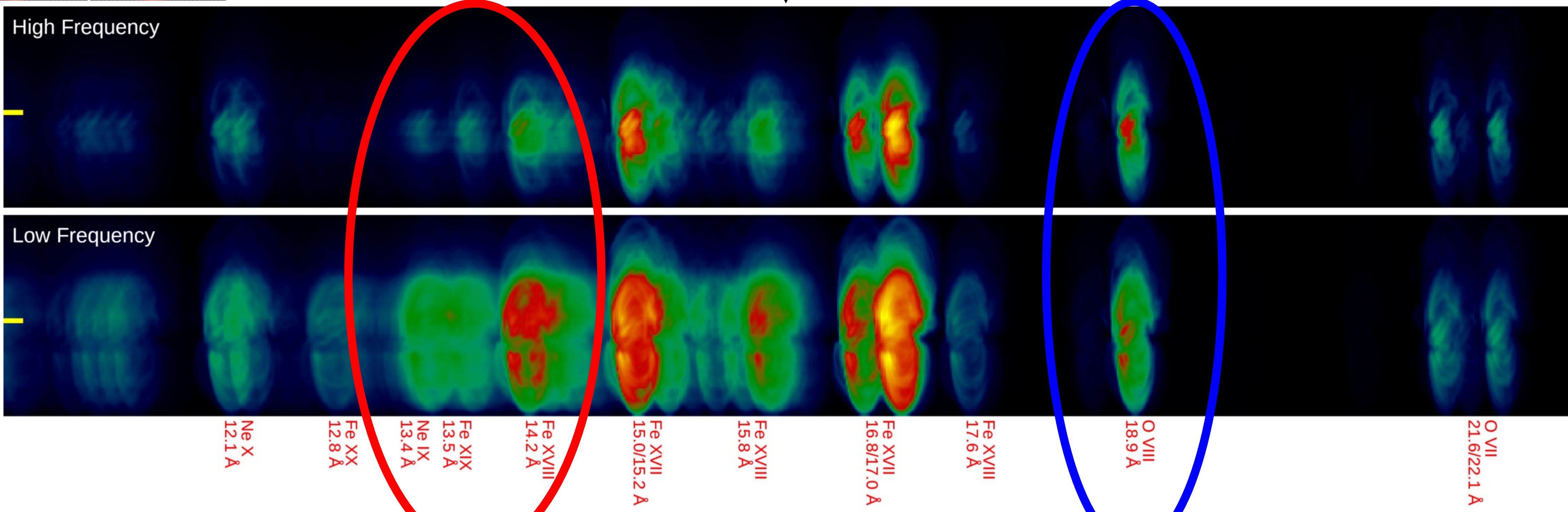
Spectrally pure images of the Sun overlap and are squashed in spectral direction



MaGIXS data are "Overlappograms"



Some spectral lines look similar, others look different based on the two heating models.



MaGIXS Launch – July 30, 2021

~18:20 UT
~296 s science data

MaGIXS Launch – July 30, 2021

~18:20 UT
~296 s science data

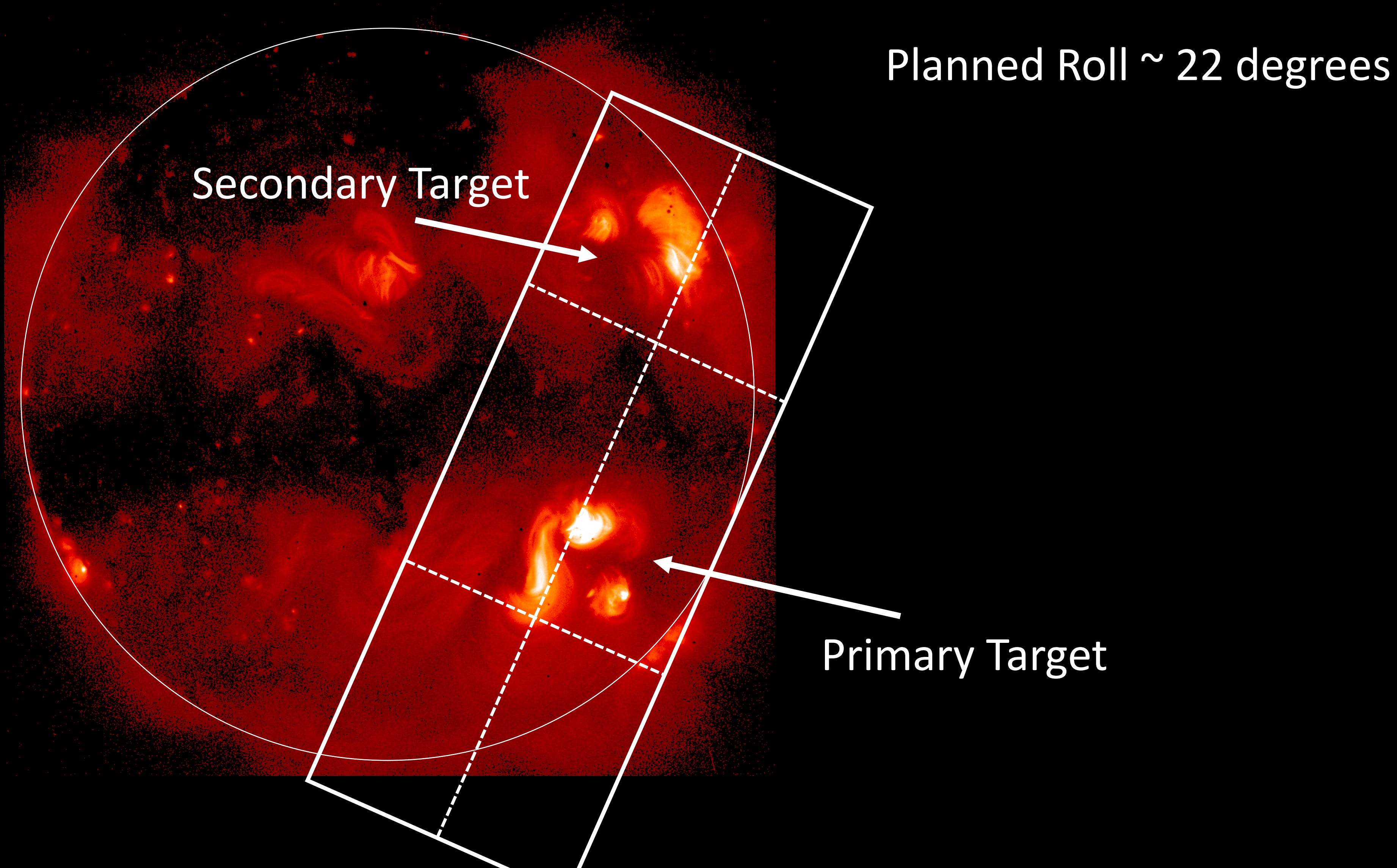
MaGIXS Launch – July 30, 2021

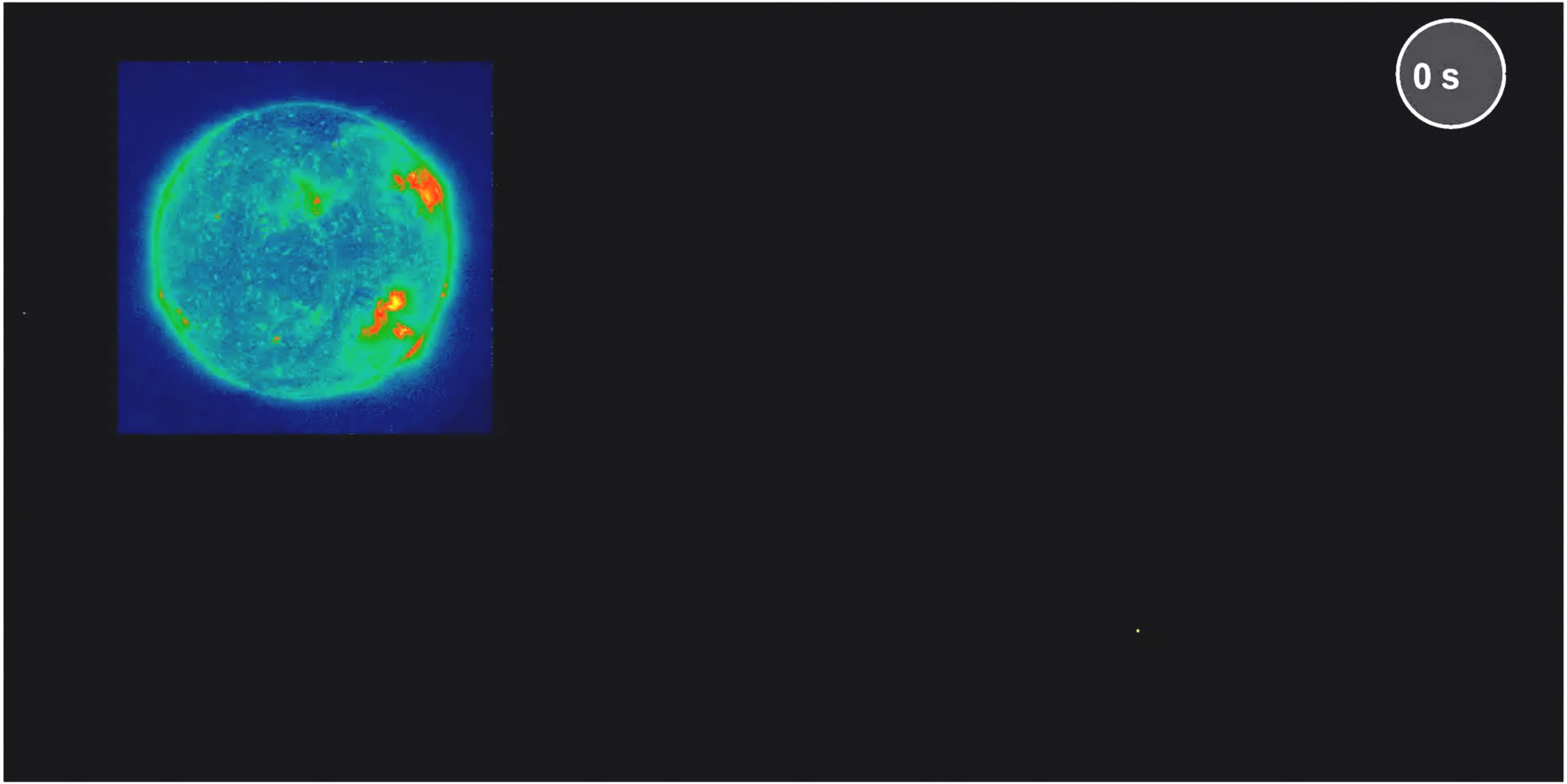
~18:20 UT
~296 s science data

MaGIXS Launch – July 30, 2021

~18:20 UT
~296 s science data

MaGIXS Targets




0 s

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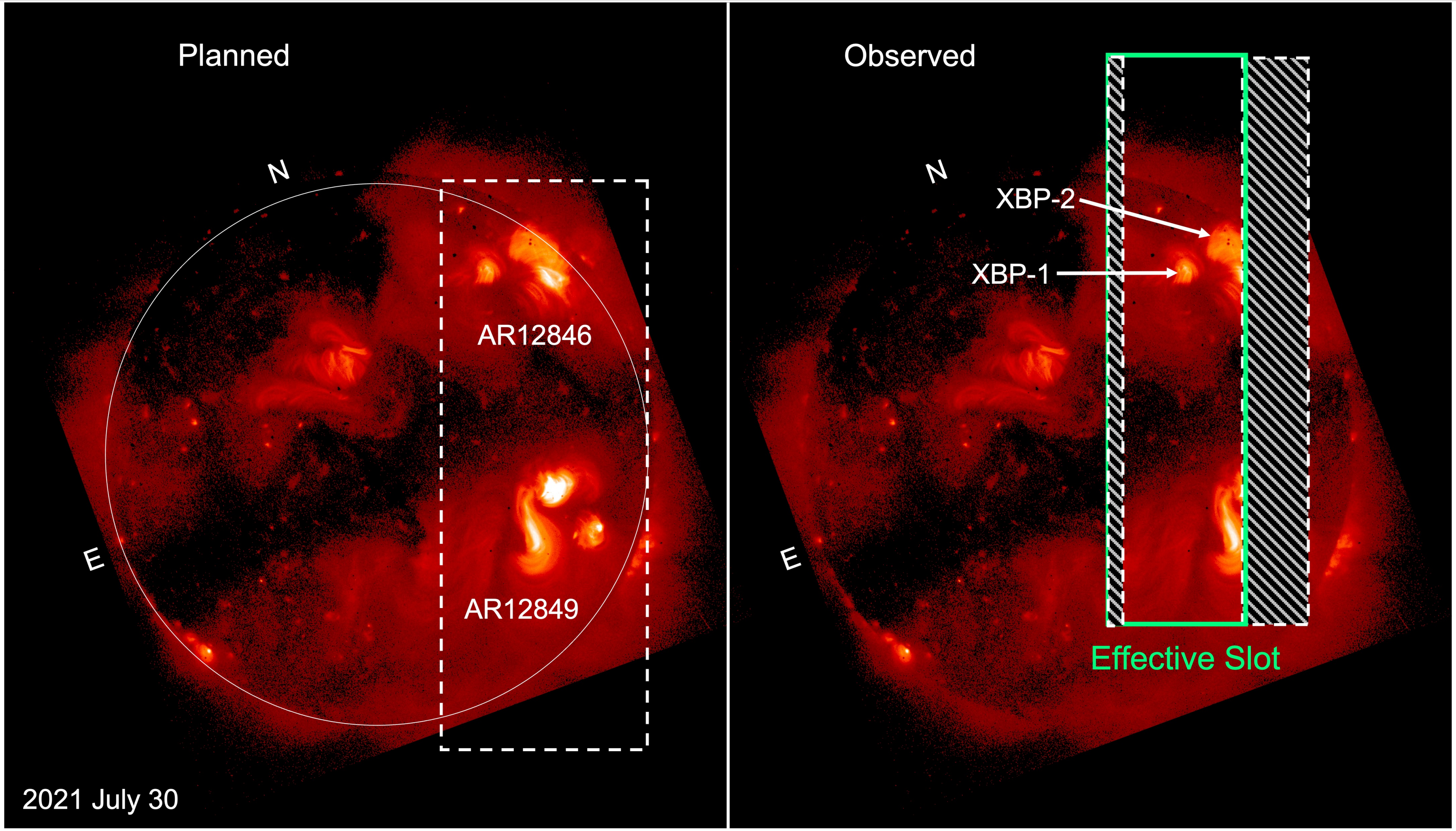
MaGIXS Flight Summary

30 July 2021, ~18:20 UT
~296 s science data

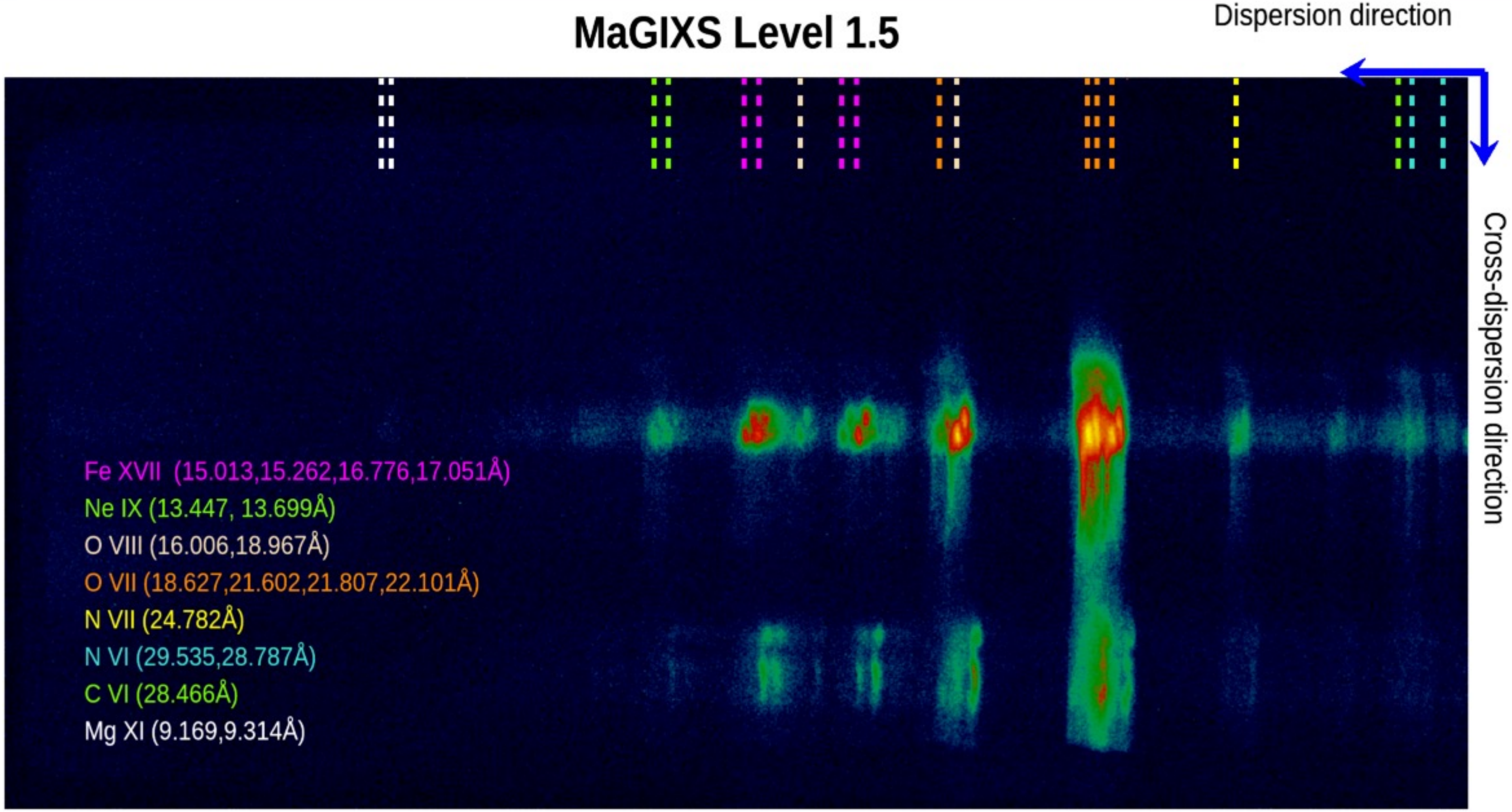


Actual observations show:

- Internal vignetting in the system
- Slot was offset
- Hot regions of the targets were missed
- Observed X-ray bright points

MaGIXS Flight Data

~18:20 UT
~296 s science data



MaGIXS data are "overlappograms"

Observed several warm emission lines 1 to 4 MK plasma

Savage et al., 2023,(acc. ApJ)

Unfolding method

Write a set of linear equations:

Observations = Response Matrix # EM(space, temperature, density, abundance)

$$y = Mx$$

Response Matrix includes:

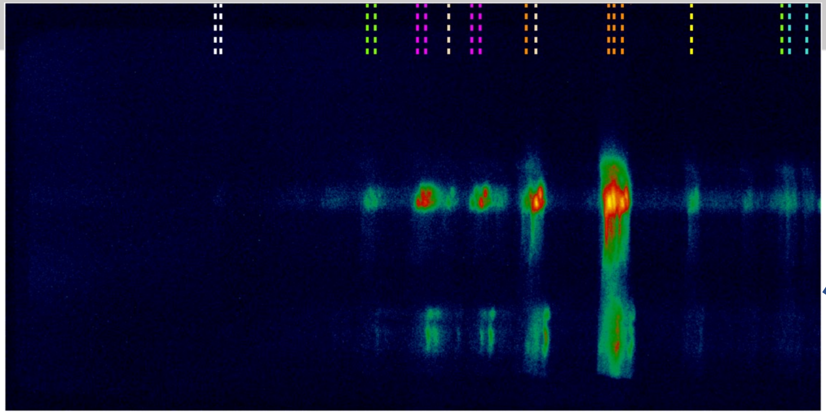
- Atomic data – How does the solar plasma radiate?
- Instrument response – How does the instrument measure the radiation?

Generally $N_{EM} >> N_{obs}$, additional assumptions required to solve.

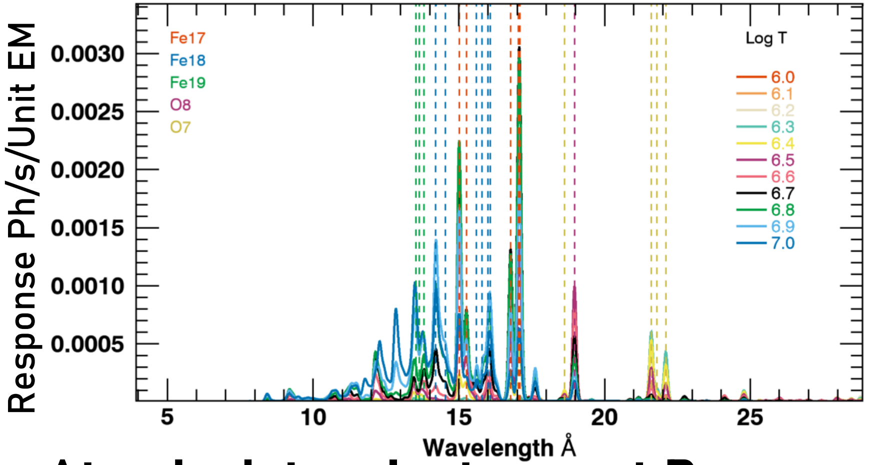
We assume a ***sparse inversion***.

MaGIXS Inversion

Inputs



Overlappogram



Atomic data + Instrument Response

Inversion Algorithm

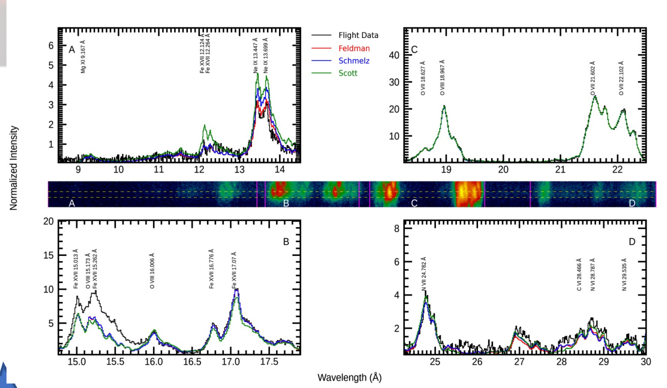
EM cubes

LASSOLARS ELASTIC NET (available from scikit in python)

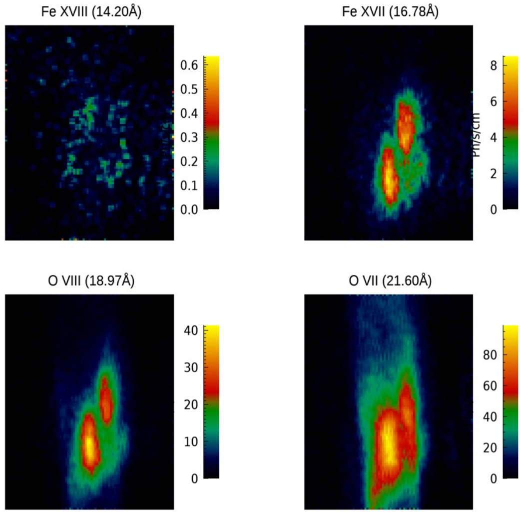
y= Mx

$$x^{\#} = argmin\left[||y - Mx||_2^2 + \underbrace{\alpha\rho||x||_1}_{\text{sparse}} + \underbrace{0.5\alpha(1-\rho)||x||_2^2}_{\text{smooth}} \right]$$

Outputs



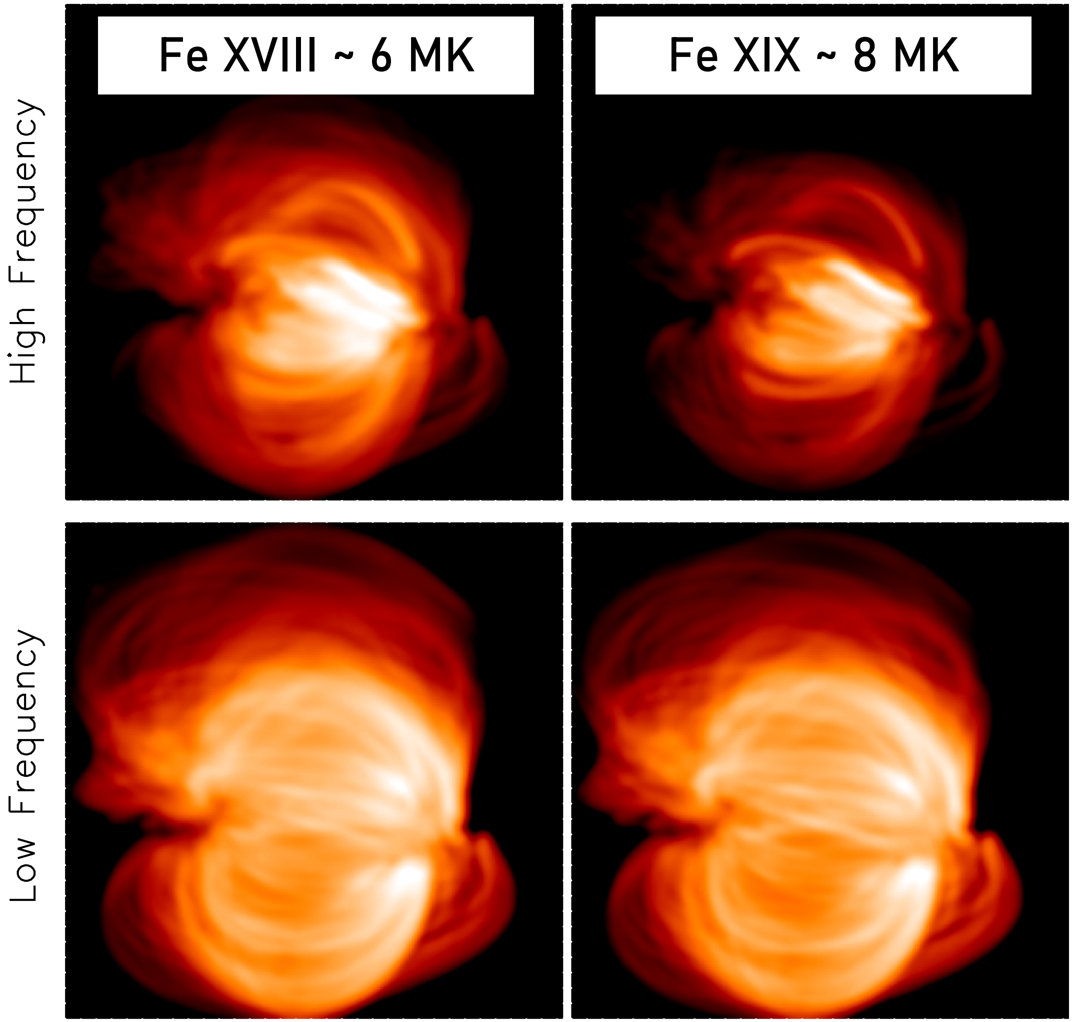
Fitted spectra

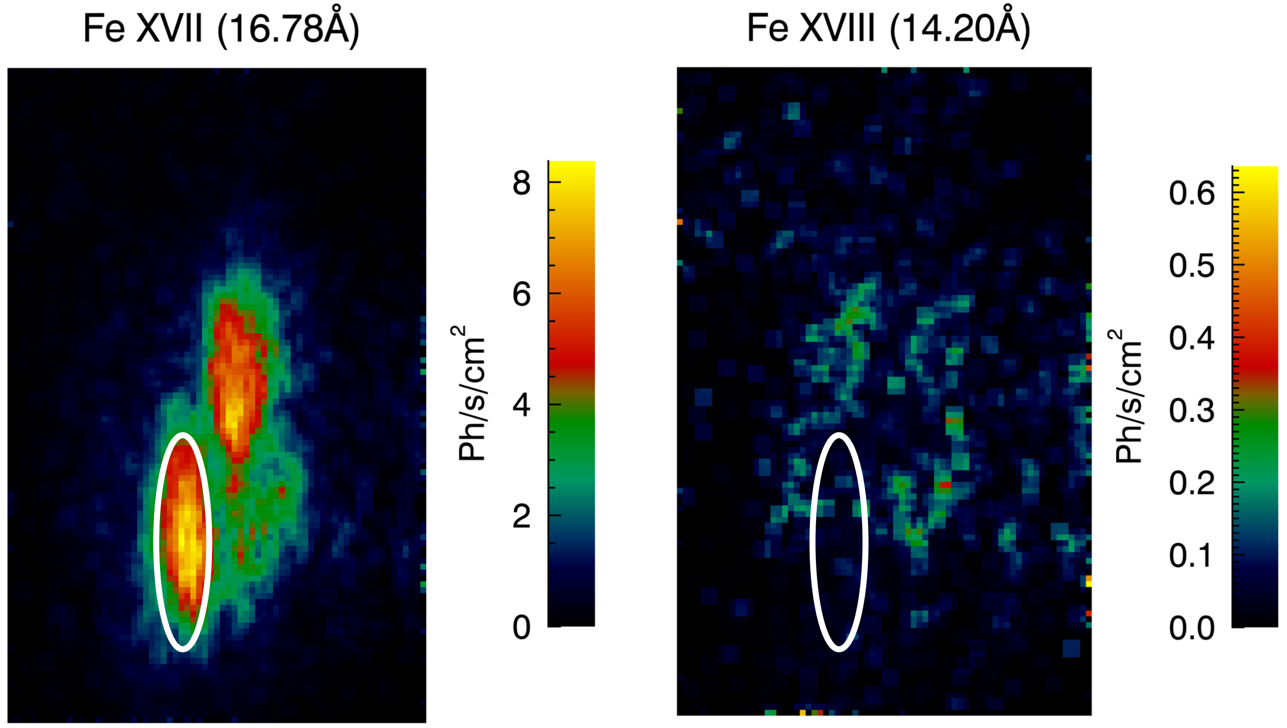


Spectrally Pure Maps

Cheung et al, De Pointeu et al, Winebarger et al 2019

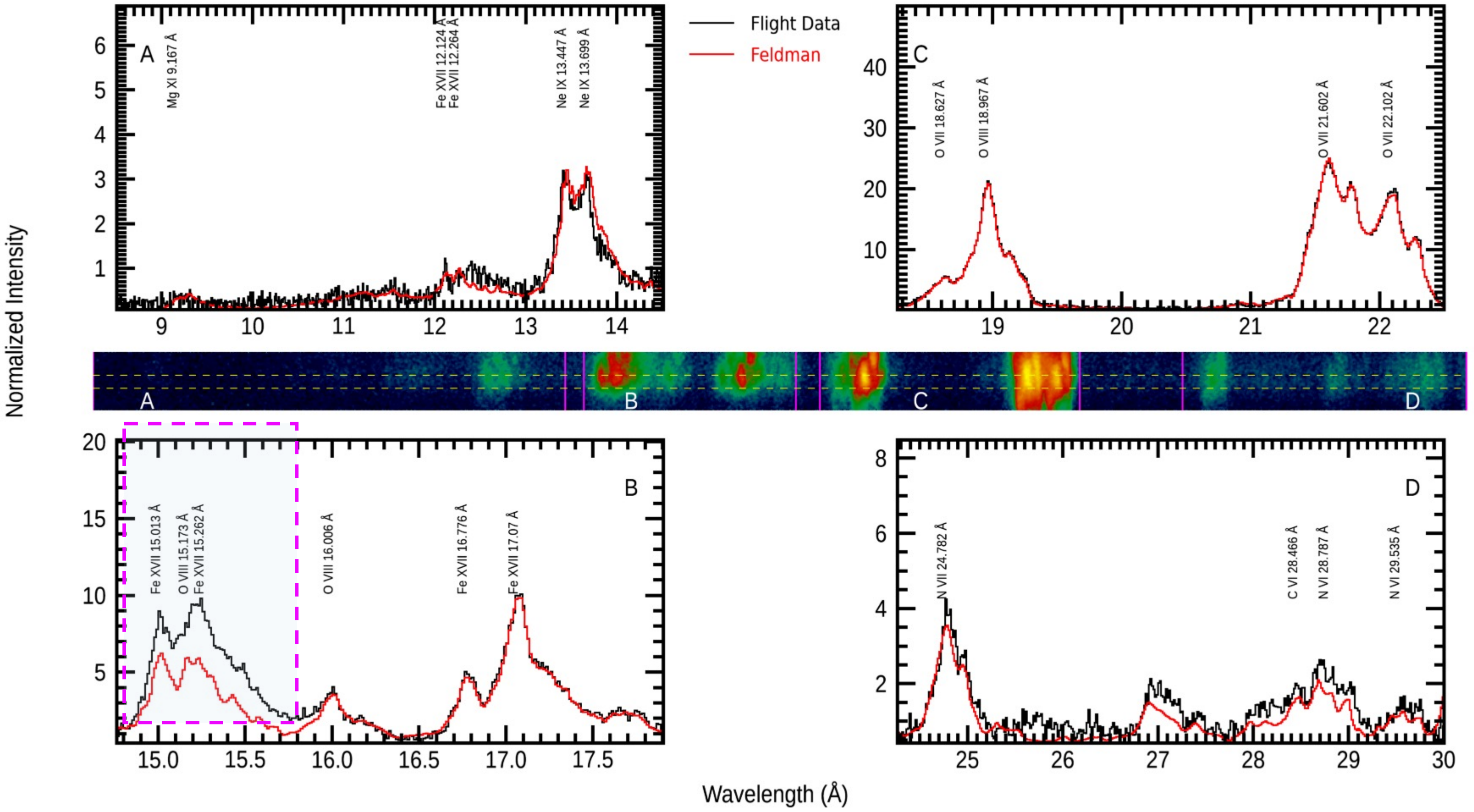
Discriminating Observations





MaGIXS observations support high frequency (wave) heating!

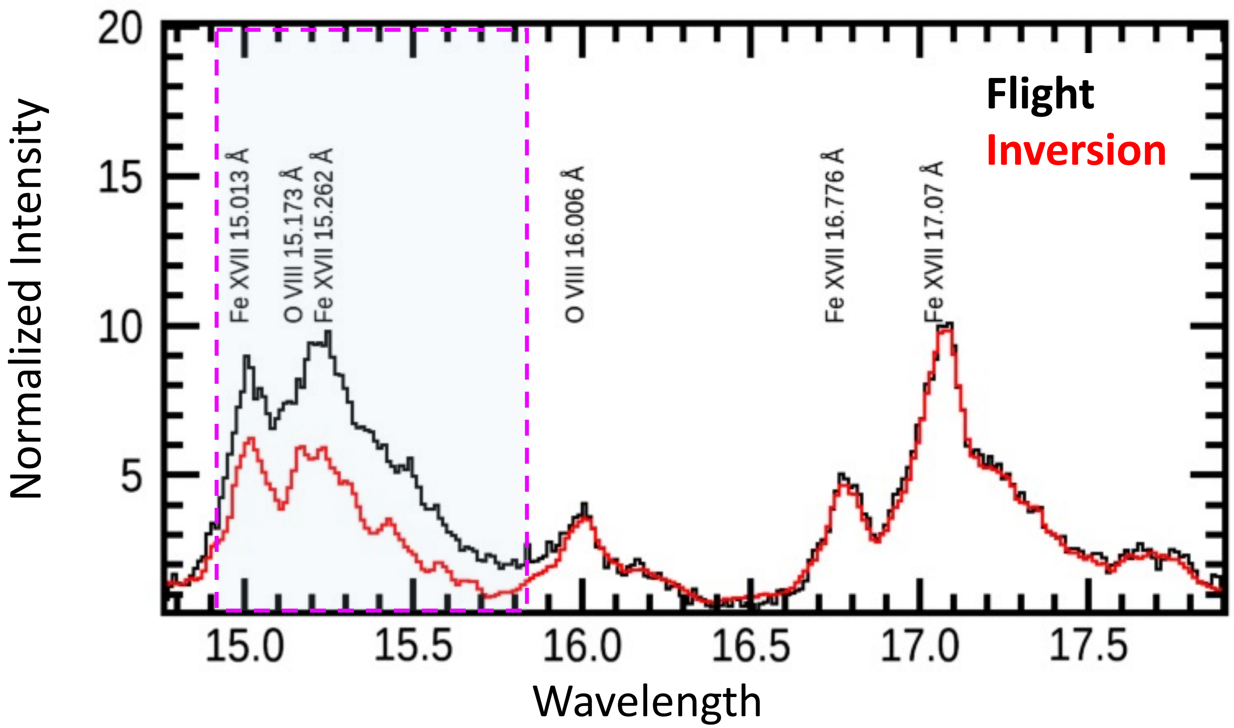
MaGIXS inversion : Excess Emission near 15Å

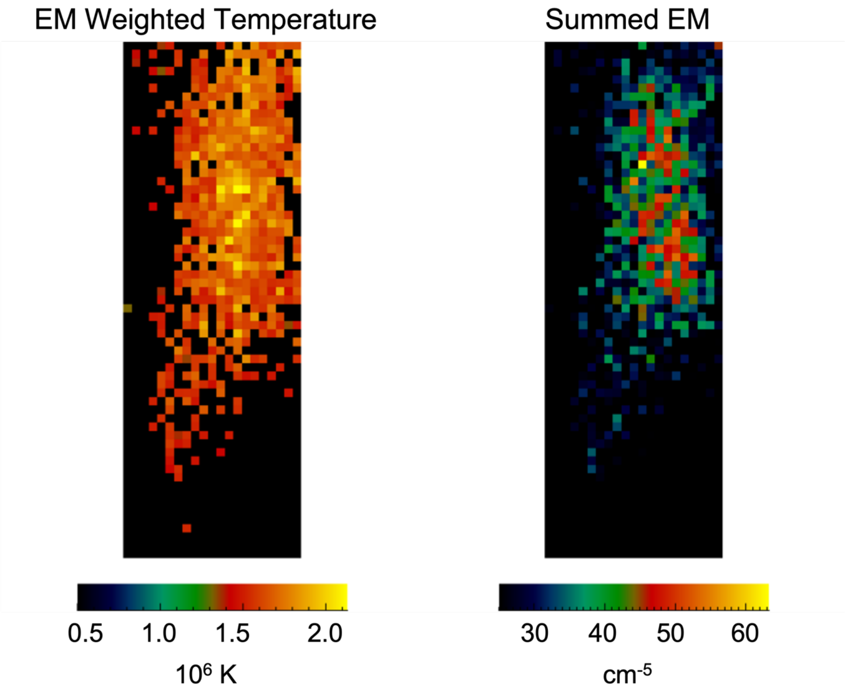


- MaGIXS observed excess emission in the 15-15.7Å over inversion
- Inversion consistently underestimate intensity regardless of inversion parameters

Savage et al., 2023,(accepted ApJ)

MaGIXS inversion : Excess Emission near 15Å





Reason : Some Satellite lines of Fe XVII, Fe XVI and Fe XV are missing in CHIANTI

EM weighted temperature reveal dominant “Relatively Cool” (2 MK) plasma

MaGIXS Results and Future Work

MaGIXS-1 met comprehensive success criteria

- Analysis of Spot 1 shows region is consistent with high-frequency heating.

However,

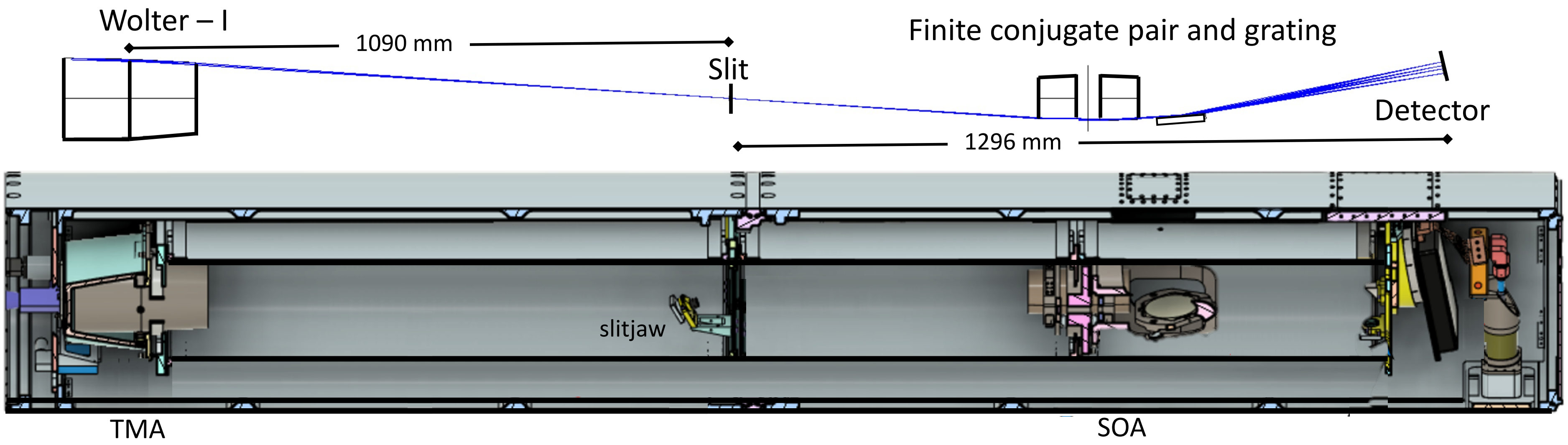
- MaGIXS-1 observations were limited by vignetting function and missed the majority of the primary target.
- Observations included two bright points and one loop structure, not the active region core as proposed.
- Low flux limited the conclusions.

MaGIXS-1 was recovered.
MaGIXS-2 will launch in 2023.

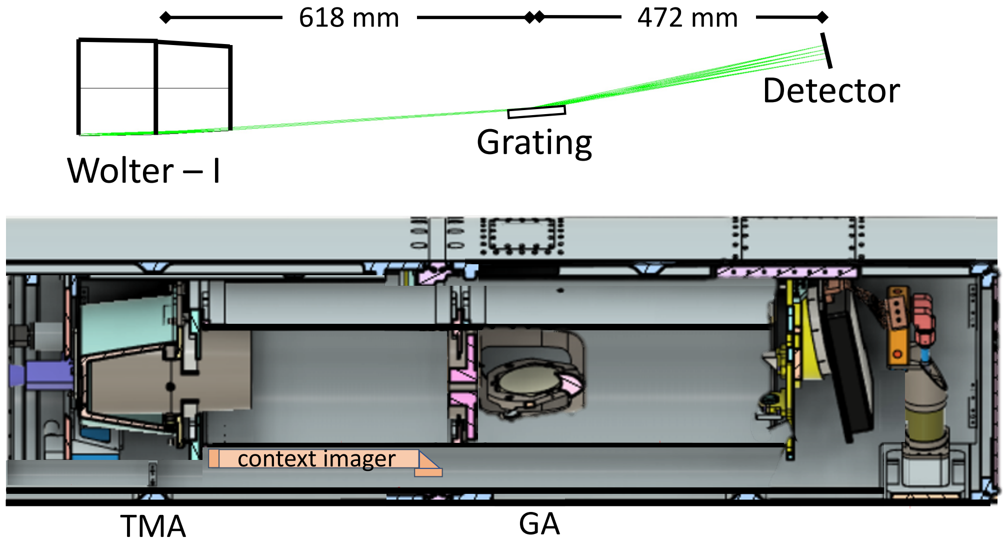
Savage et al,. 2012 (MaGIXS Mission Paper)

MaGIXS-2 instrument changes

MaGIXS-1



MaGIXS-2



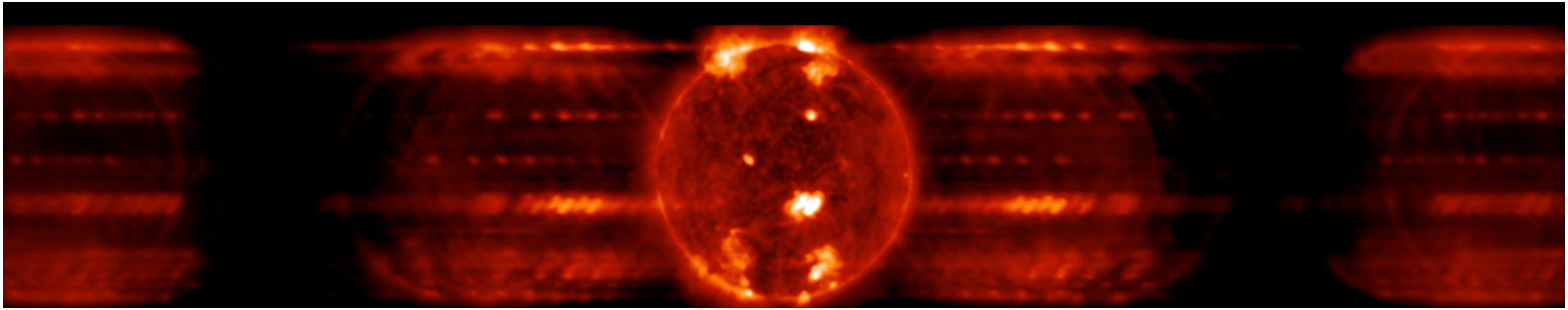
MaGIXS–2 will have

- Easier alignment process
- Better spatial resolution (x4)
- Better spectral resolution (x4)
- Larger FOV (4′ –> 12′)
- Higher throughput

Conclusions

- Slitless Imaging Spectrograph provide valuable spectroscopic data over large field of view at a rapid cadence.
- Advances in computing efforts and machine learning unlock the potential of these instruments.
- Sounding rockets are paving the way to new satellite instruments.

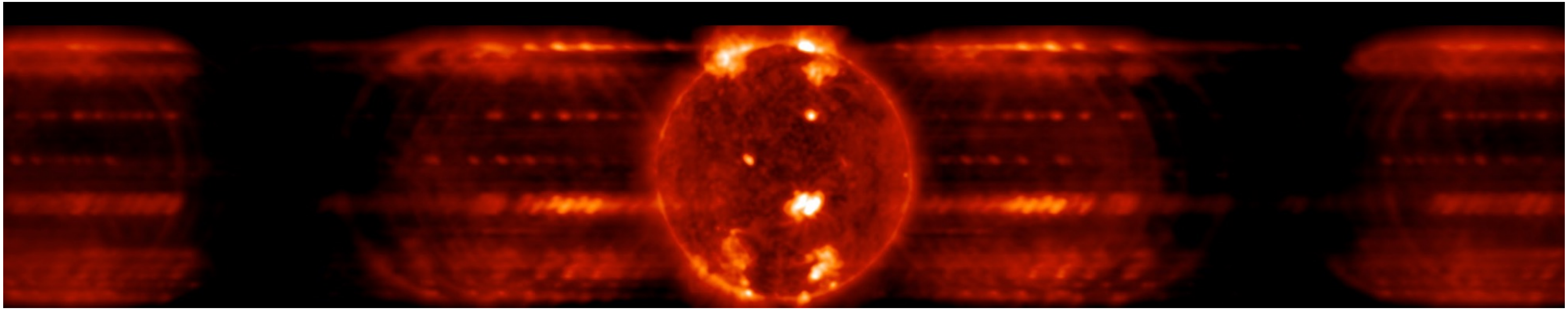
Summary



Expected MOXSI data

“Therefore this image is not easy to interpret.” - R. Tousey

Summary



Expected MOXSI data

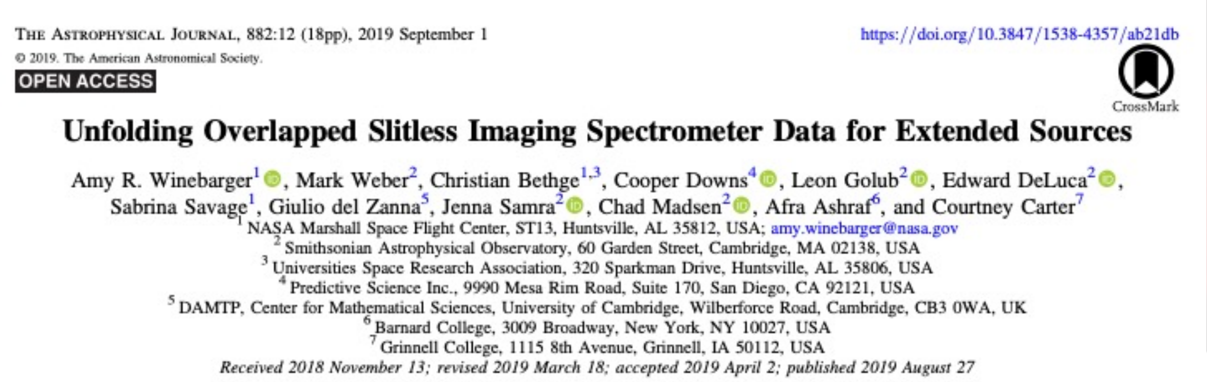
~~"Therefore this image is not easy to interpret." - R. Tousey~~

Come join the team!

- NSF Research Experience for Undergraduate Program
- NASA Undergraduate and Graduate Summer Research Programs
- Graduate student research assistants from multiple universities
- NASA Post doc positions

Back up

COSIE Example


The Astrophysical Journal, 882:12 (18pp), 2019 September 1 https://doi.org/10.3847/1538-4357/ab21db

Unfolding Overlapped Slitless Imaging Spectrometer Data for Extended Sources

Amy R. Winebarger[1], Mark Weber[2], Christian Bethge[1,3], Cooper Downs[4], Leon Golub[2], Edward DeLuca[2], Sabrina Savage[1], Giulio del Zanna[5], Jenna Samra[2], Chad Madsen[2], Afra Ashraf[6], and Courtney Carter[7]
[1] NASA Marshall Space Flight Center, ST13, Huntsville, AL 35812, USA; amy.winebarger@nasa.gov
[2] Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA
[3] Universities Space Research Association, 320 Sparkman Drive, Huntsville, AL 35806, USA
[4] Predictive Science Inc., 9990 Mesa Rim Road, Suite 170, San Diego, CA 92121, USA
[5] DAMTP, Center for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK
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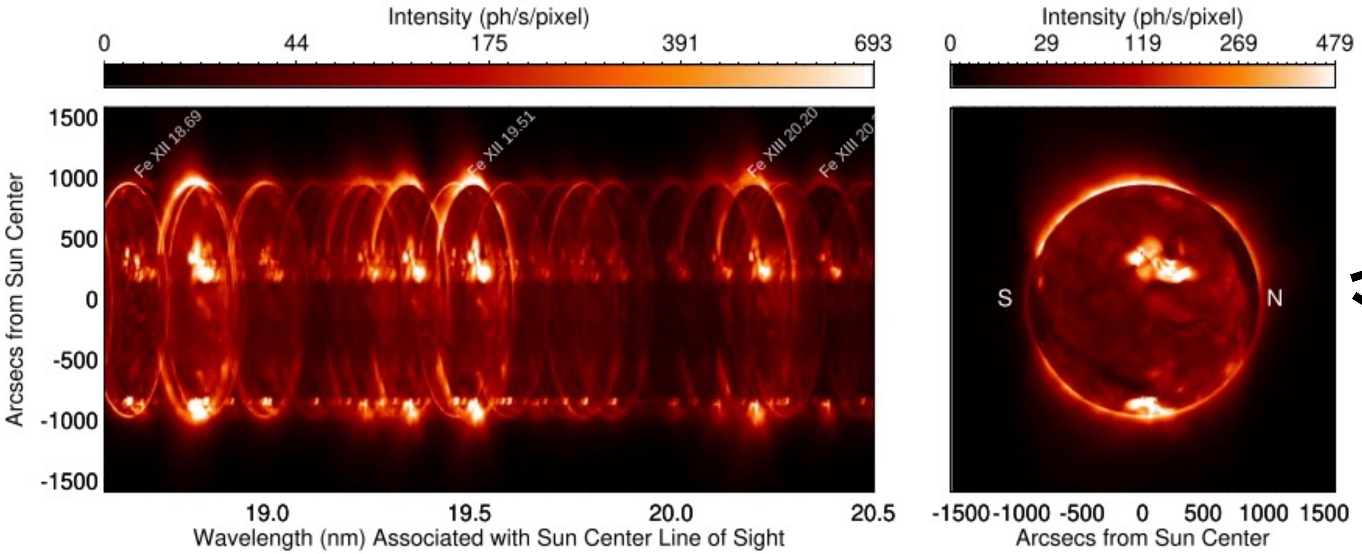
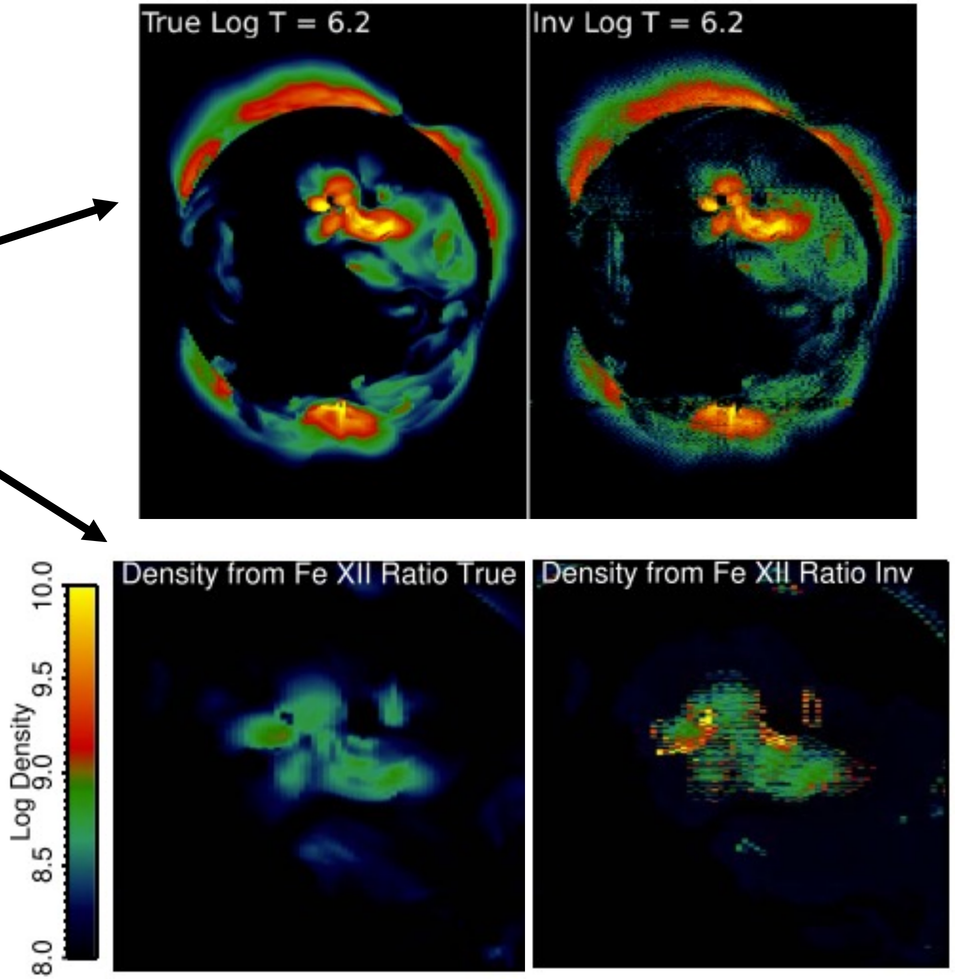
[7] Grinnell College, 1115 8th Avenue, Grinnell, IA 50112, USA
Received 2018 November 13; revised 2019 March 18; accepted 2019 April 2; published 2019 August 27





COSIE data generated from full Sun simulation

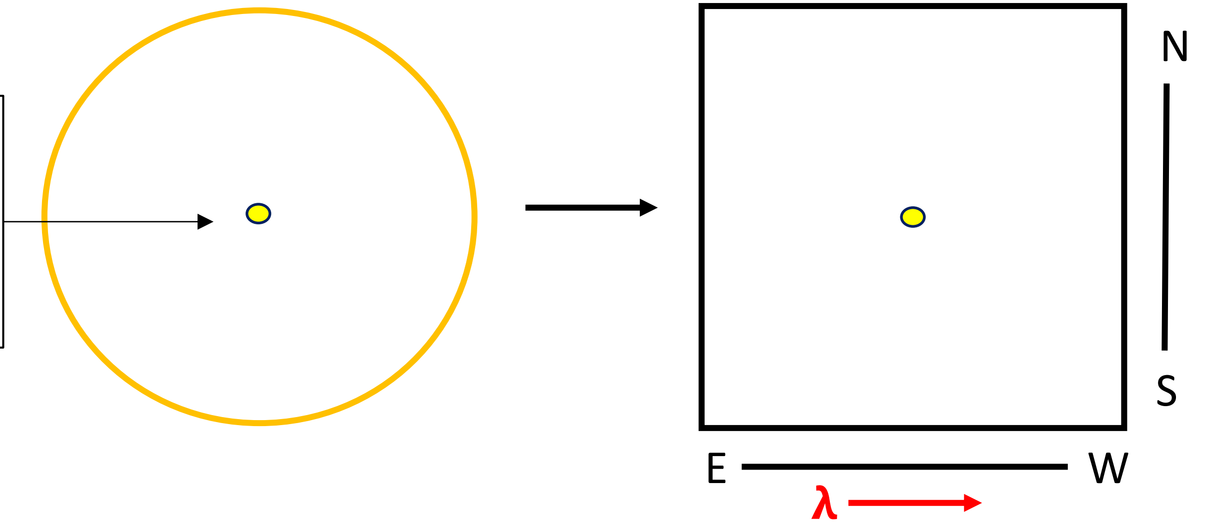
What about velocity?

- In COSIE and MOXSI, we could ***ignore velocity***.
- ESIS and COOL-AID want to ***measure velocity***.
- Both ESIS and COOL-AID are **Computed Tomography Imaging Spectrographs** (CTIS for short)

- This is a fancy name for a ***CT scan of the solar spectrum:***
  - Obtain multiple projections of the solar spectrum – dispersed at different angles – then combine to measure velocity

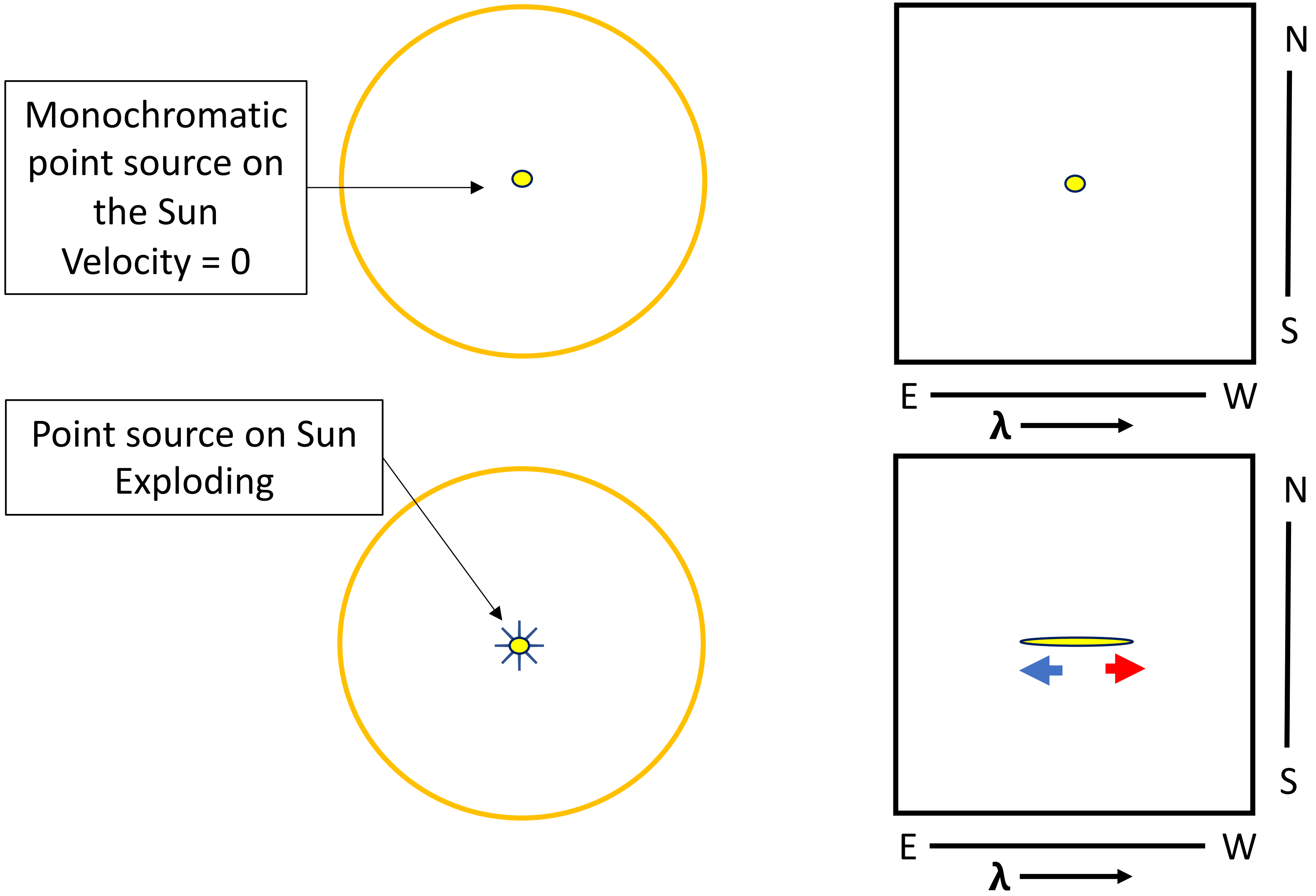
Why do we need a CTIS?

Monochromatic point source on the Sun
Velocity = 0

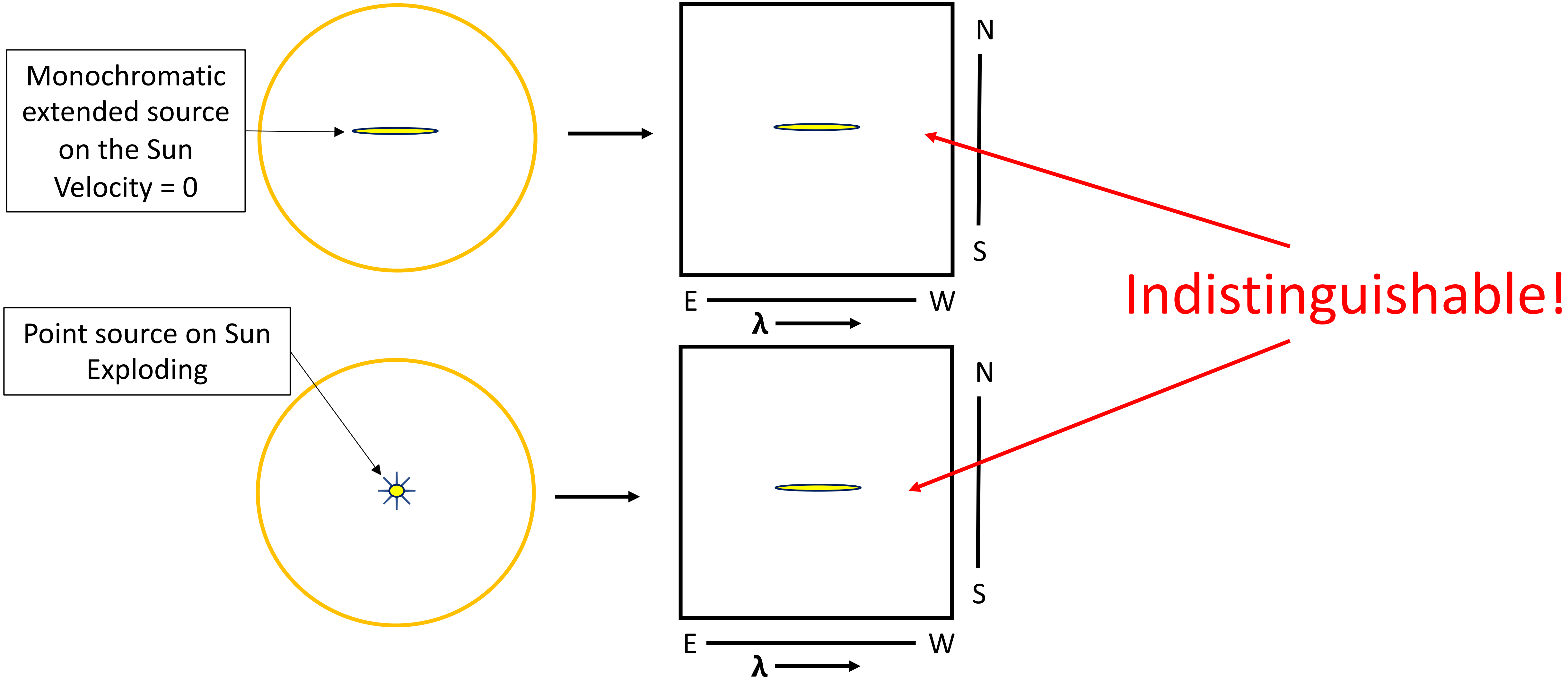


Imaged through imaging spectrograph

Why do we need a CTIS?

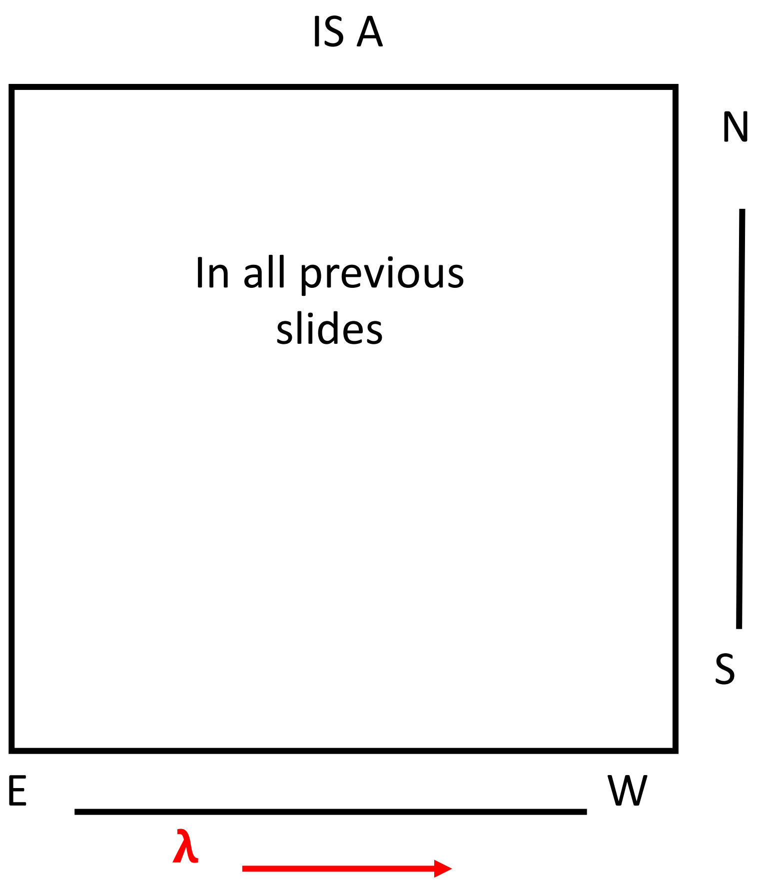


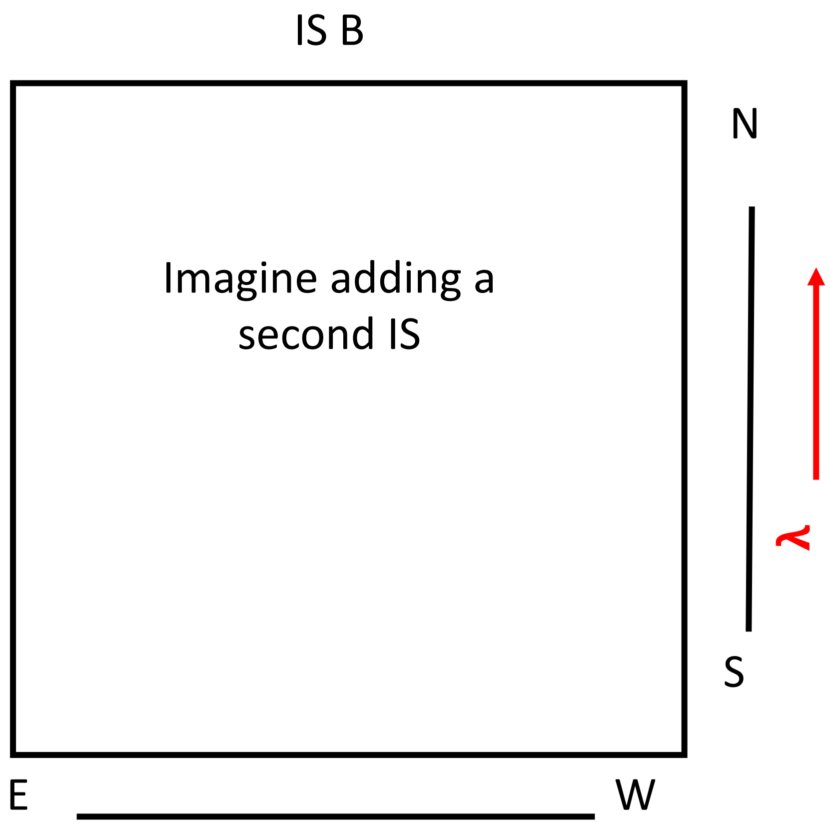
Why do we need a CTIS?



Why do we need a CTIS?

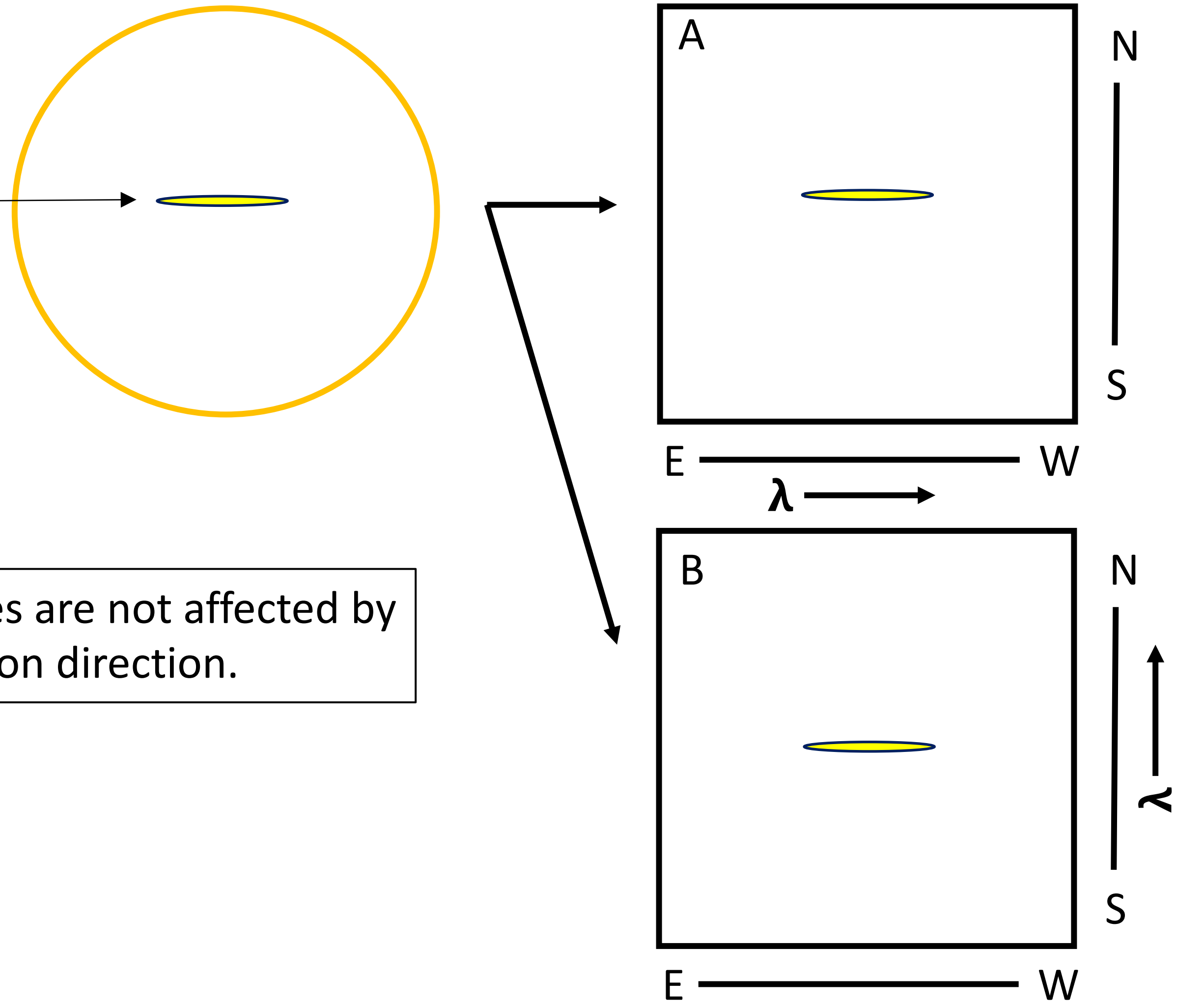
With a CTIS, we add at least one additional IS with a different dispersion direction



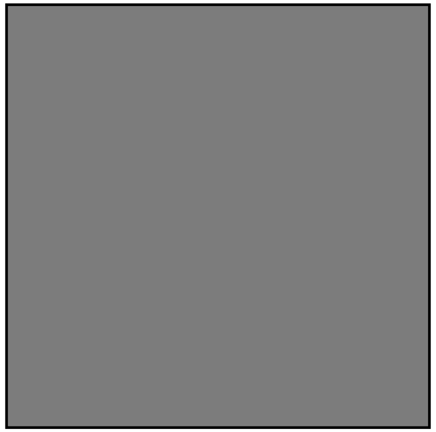


Why do we need a CTIS?

Monochromatic extended source on the Sun
Velocity = 0



IS A – IS B

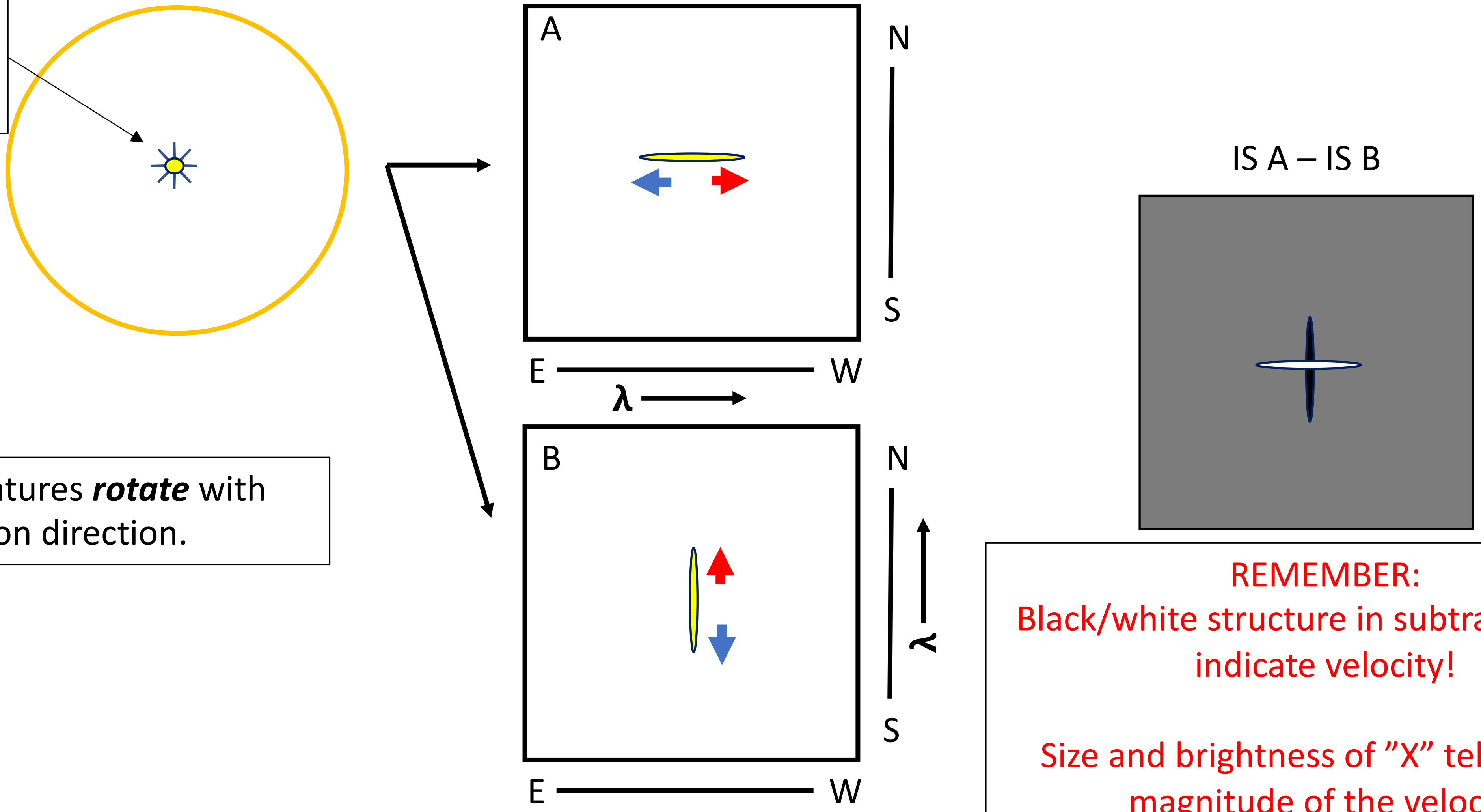


IS A – IS B = 0

Spatial structures are not affected by dispersion direction.

Why do we need a CTIS?

Point source on Sun Exploding



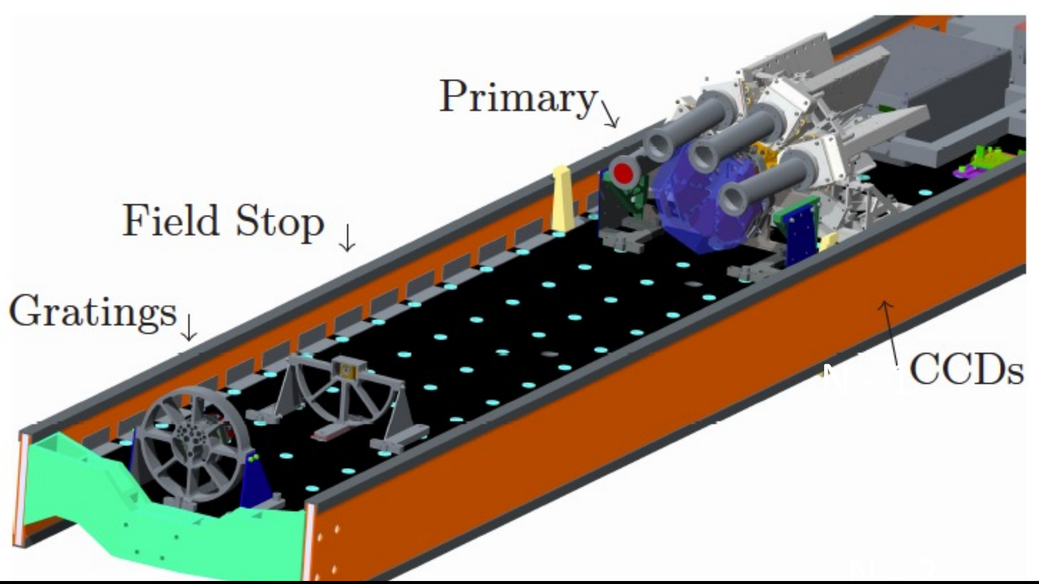
Velocity signatures ***rotate*** with dispersion direction.

REMEMBER:
Black/white structure in subtracted data indicate velocity!

Size and brightness of "X" tells us the magnitude of the velocity

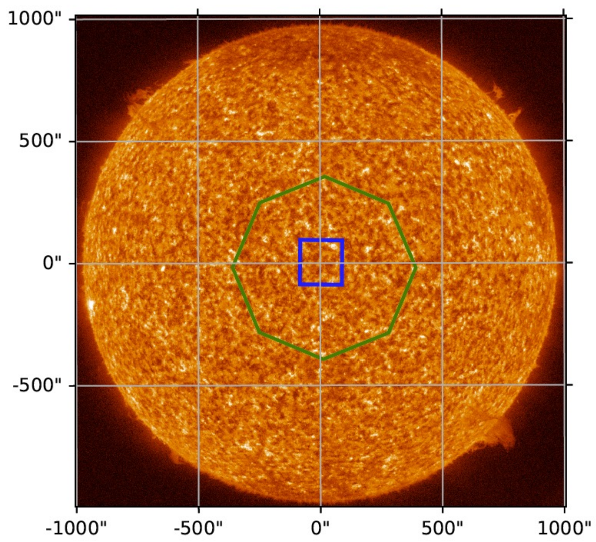
EUV Snapshot Imaging Spectrograph (ESIS)

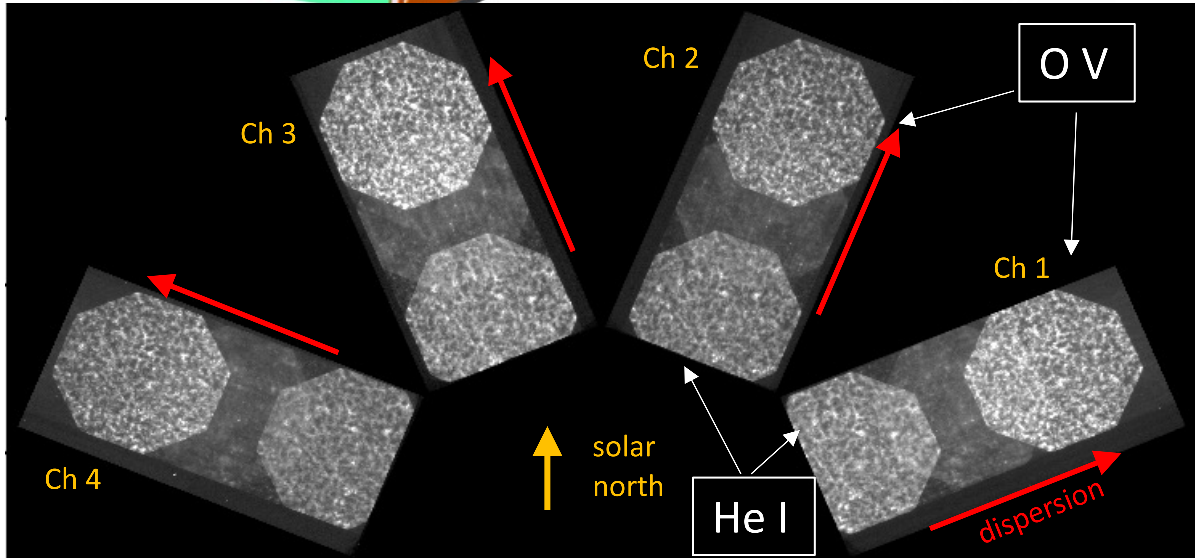
Jake Parker, Roy Smart, ESIS, and Charles Kankelborg (ESIS PI)



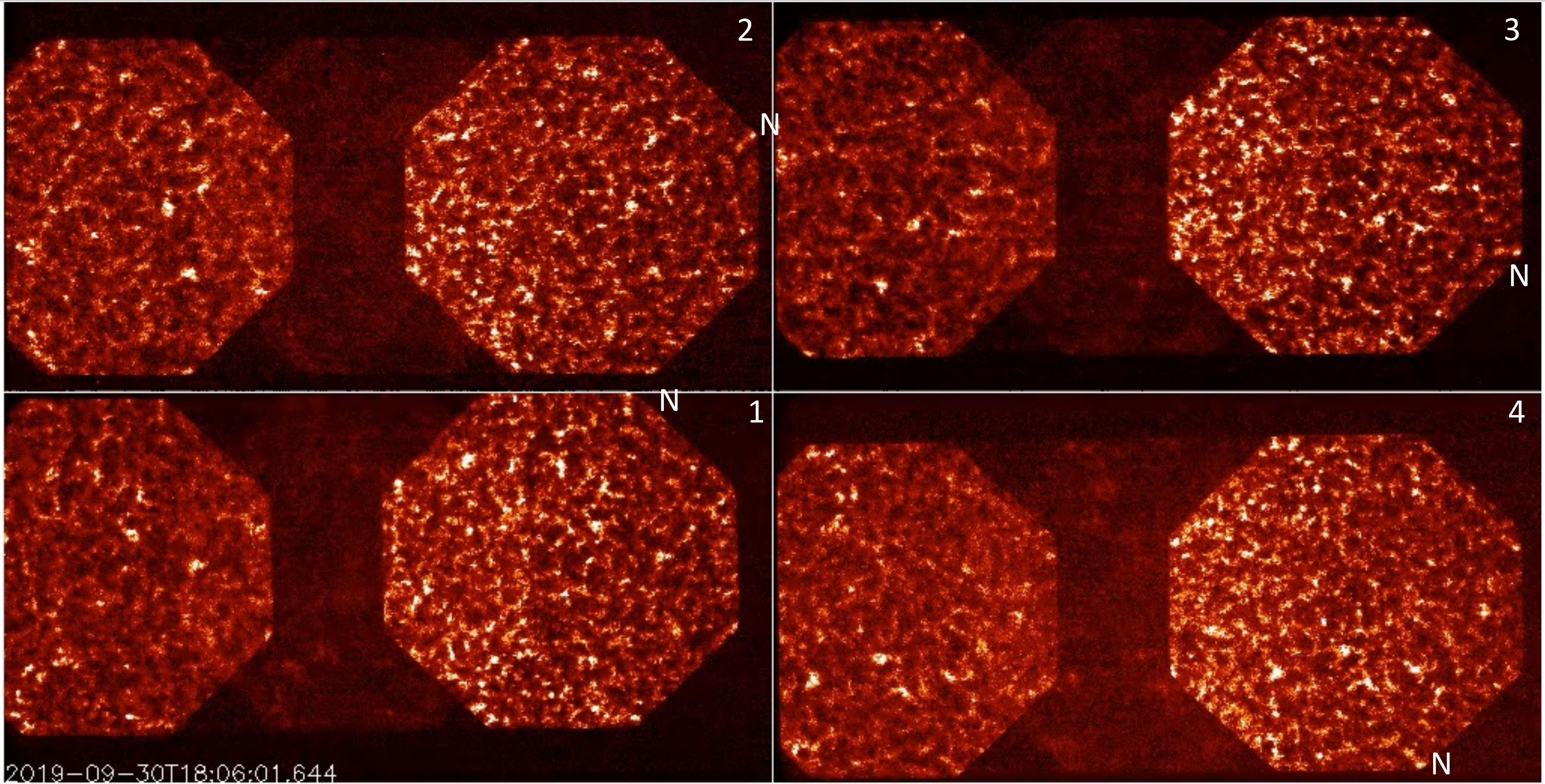
Sounding rocket instrument

- Flew September 30, 2019
- 300 s of data
- Quiet Sun
- O V 63 and He I 58.4 nm



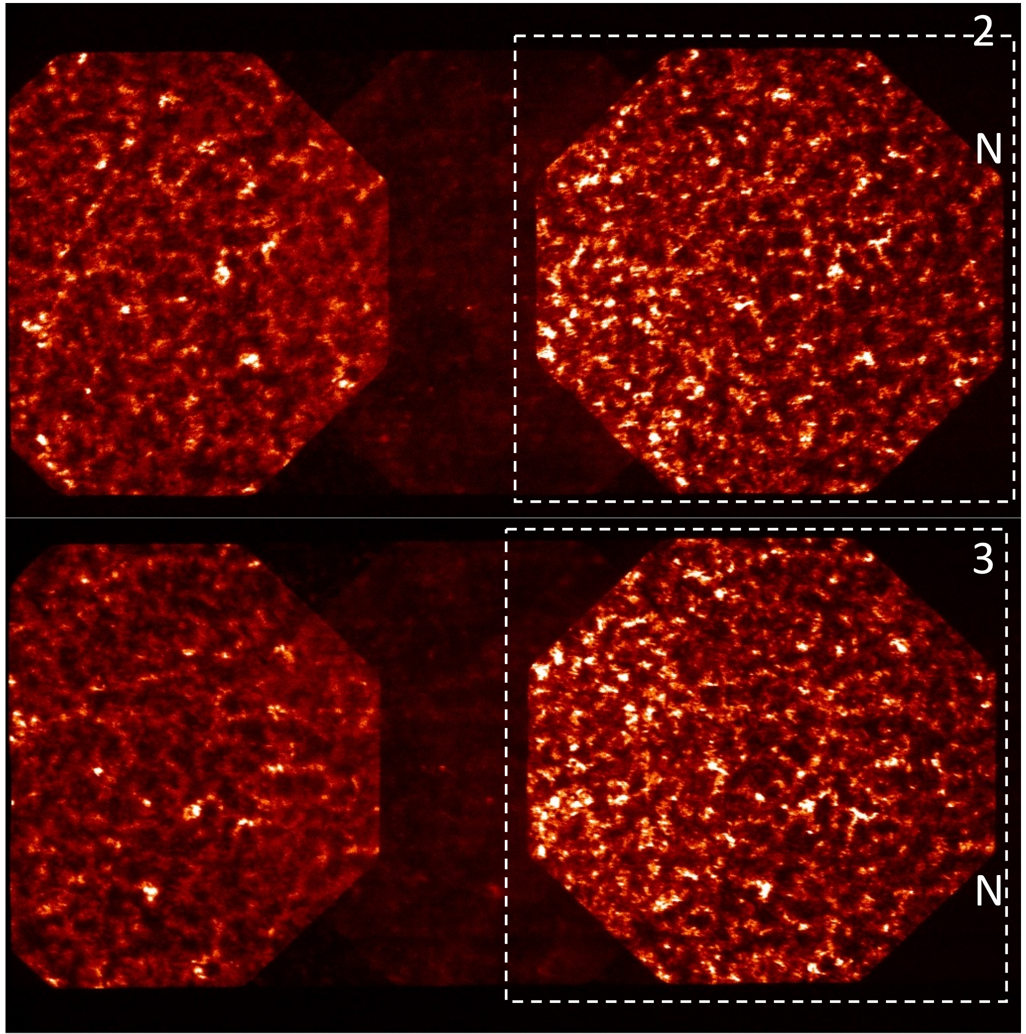


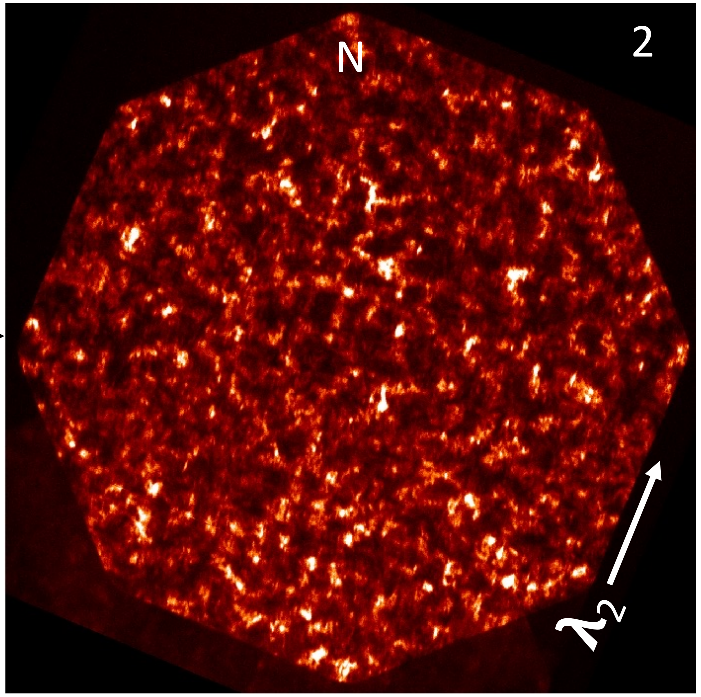
EUV Snapshot Imaging Spectrograph (ESIS)



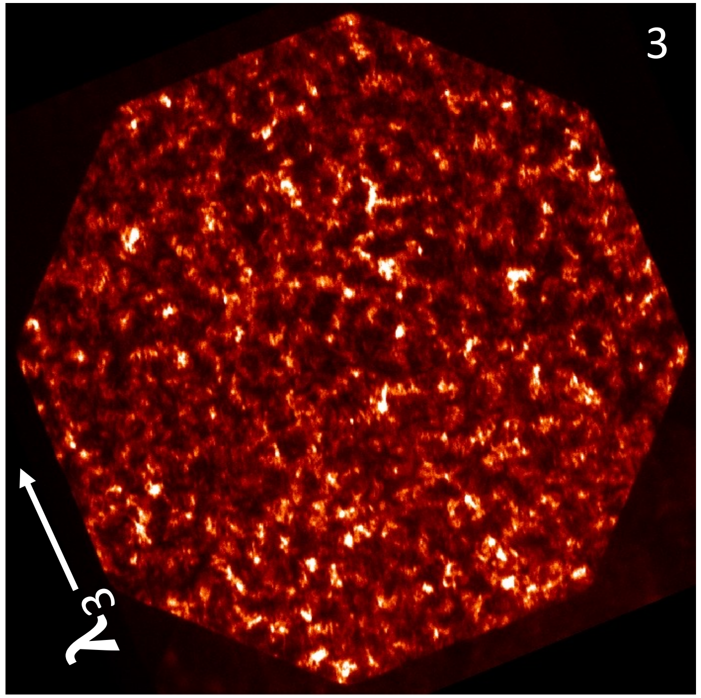
ESIS Data Processing

Level 1 data





Level 2 data
O V spectral line

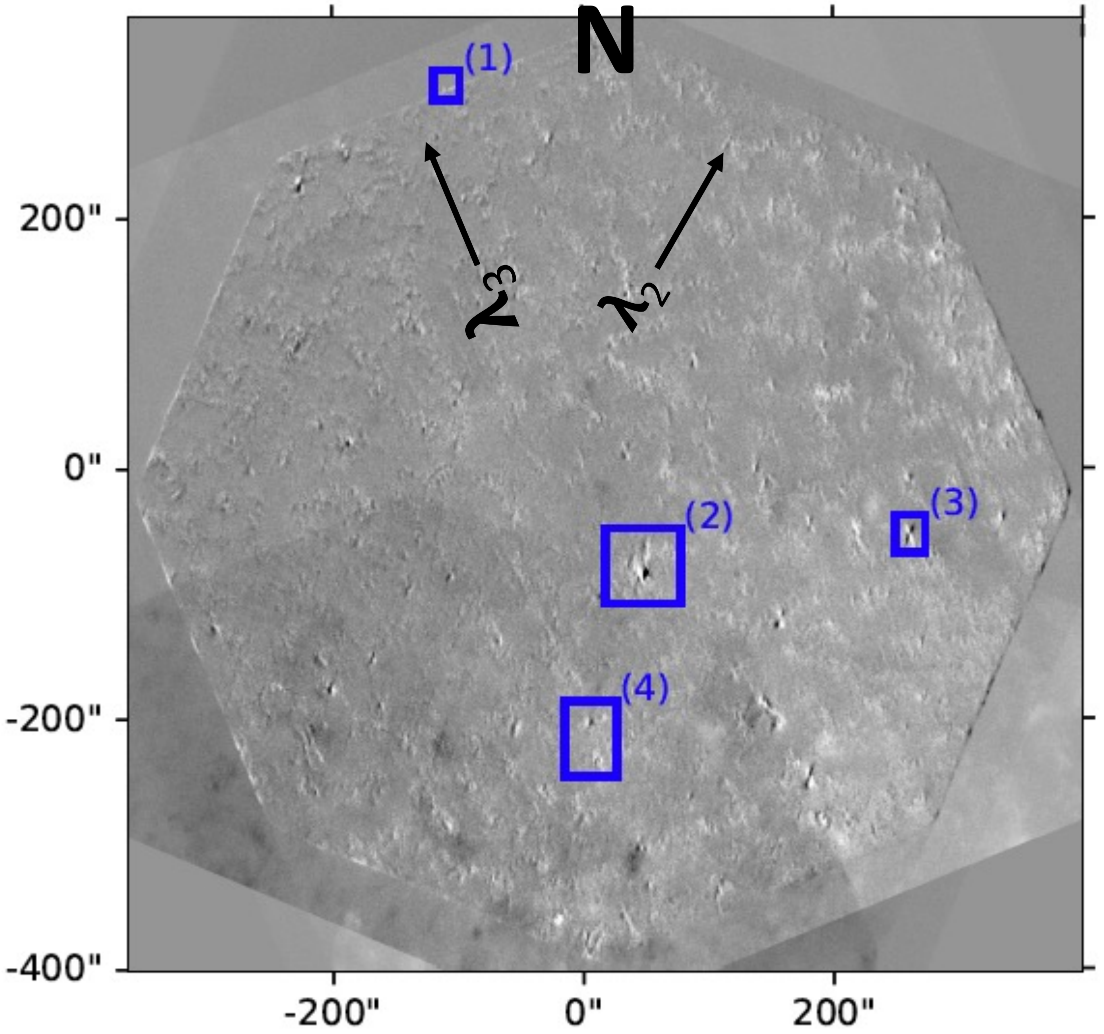


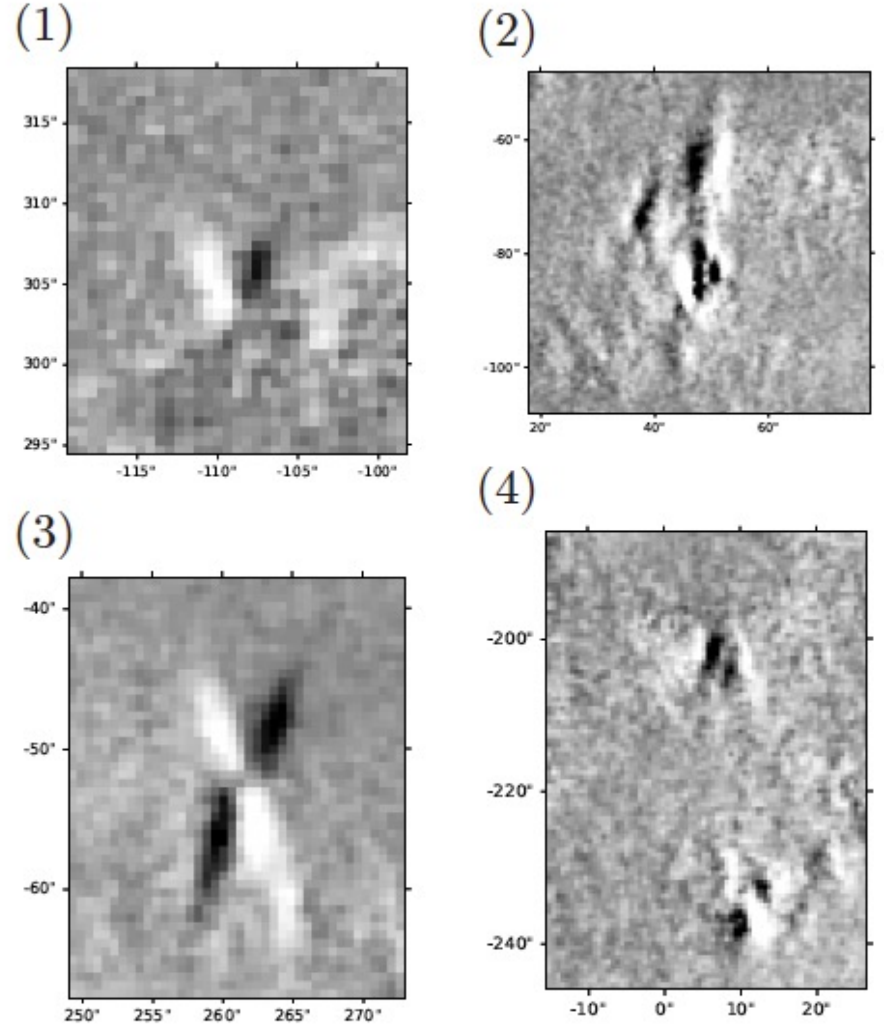
Level 2 data processing:

- Remove optical distortions & vignetting
- Extract single spectral line
- Rotate solar north is up

Images courtesy of Jake Parker, MSU

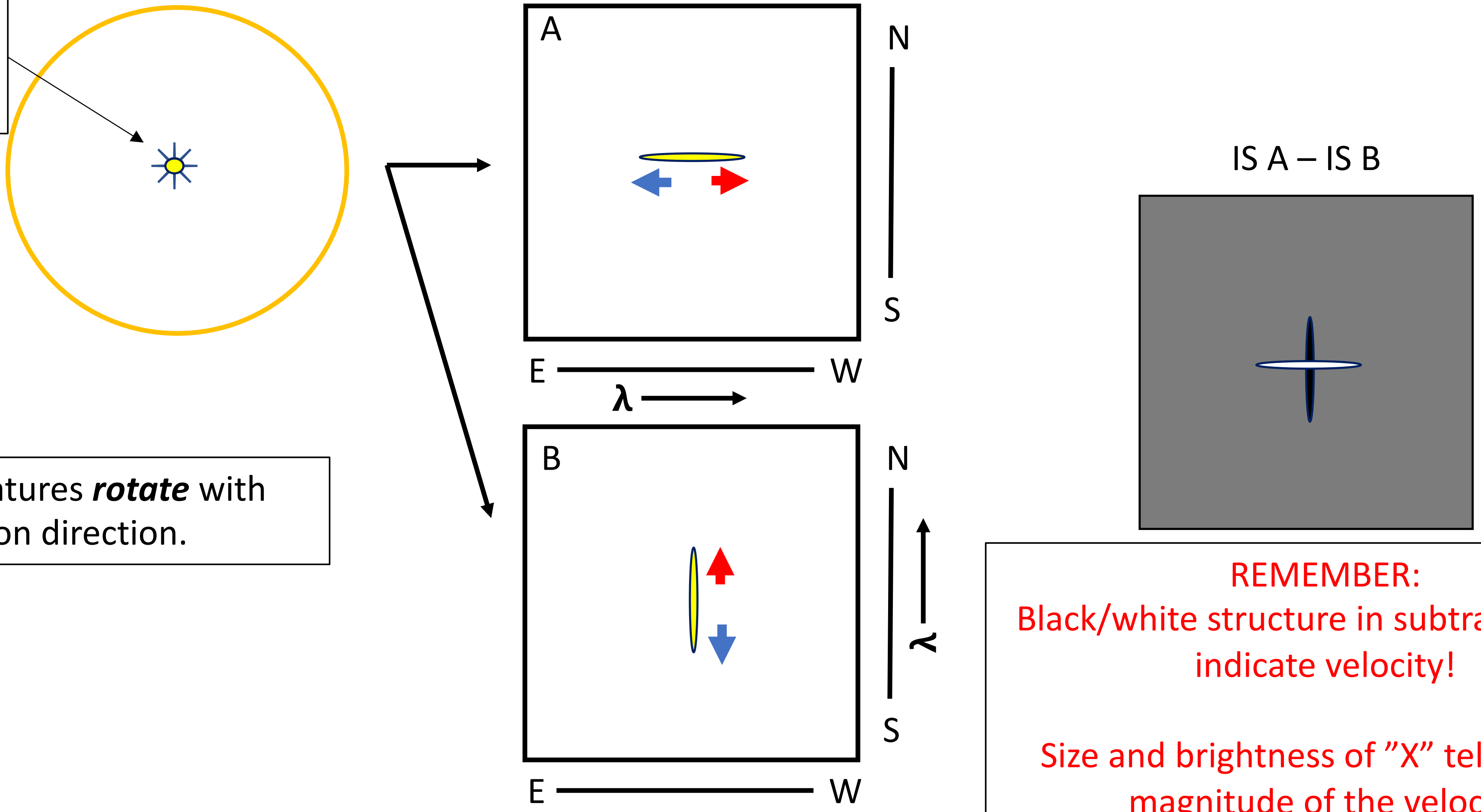
ESIS Difference Images – IS 3 – IS 2





Remember

Point source on Sun Exploding

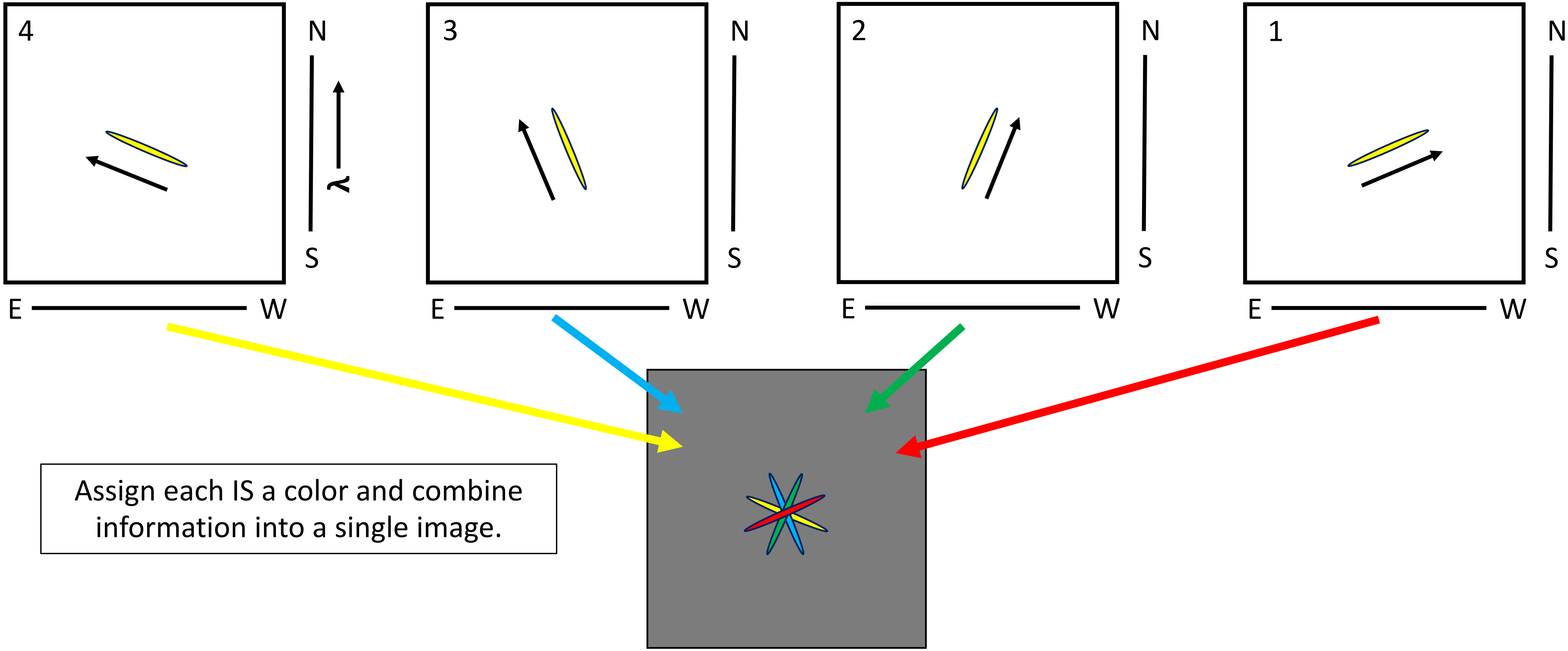


Velocity signatures ***rotate*** with dispersion direction.

REMEMBER:
Black/white structure in subtracted data indicate velocity!

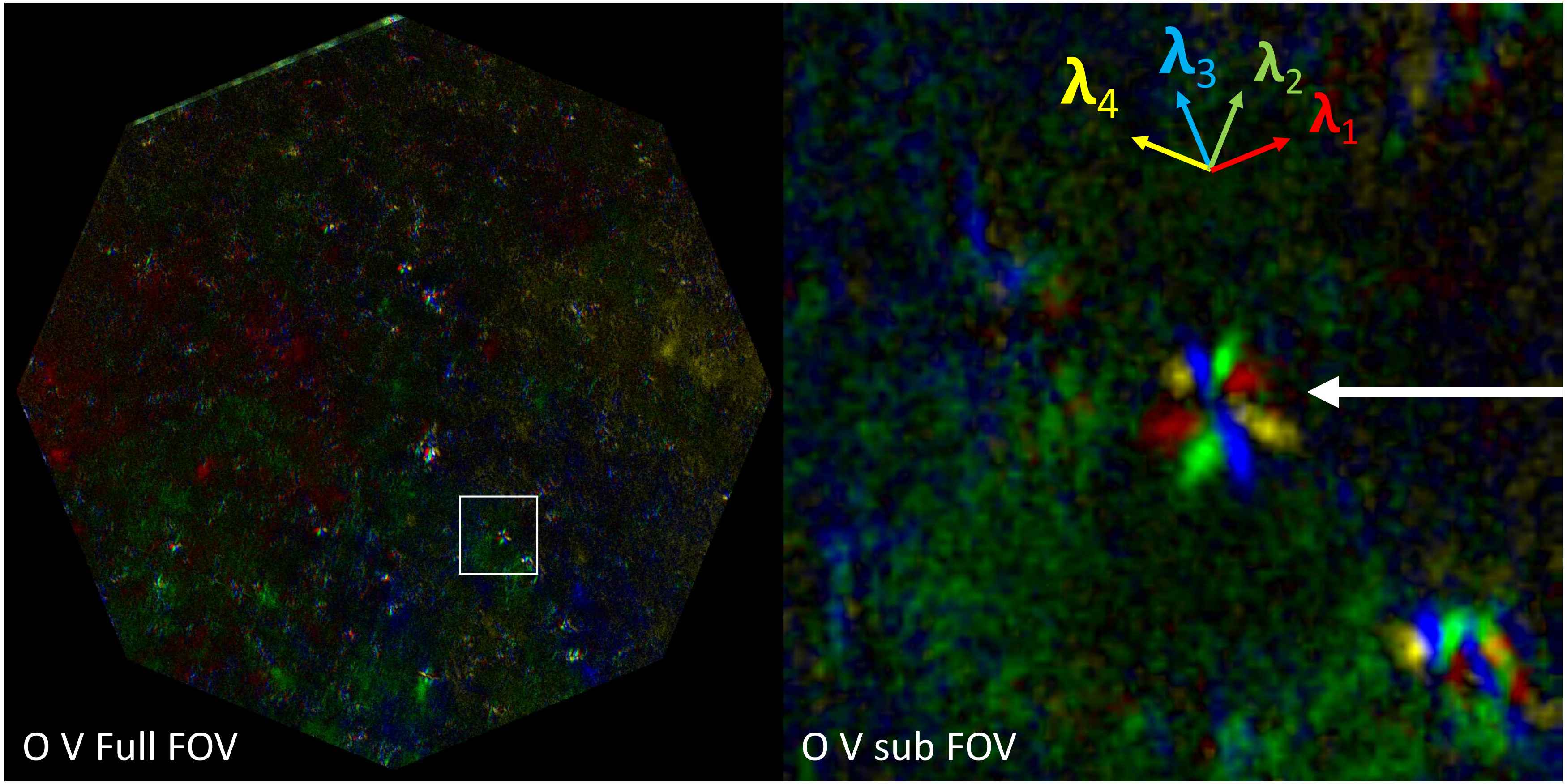
Size and brightness of ”X” tells us the magnitude of the velocity

But ESIS has 4 Imaging Spectrographs

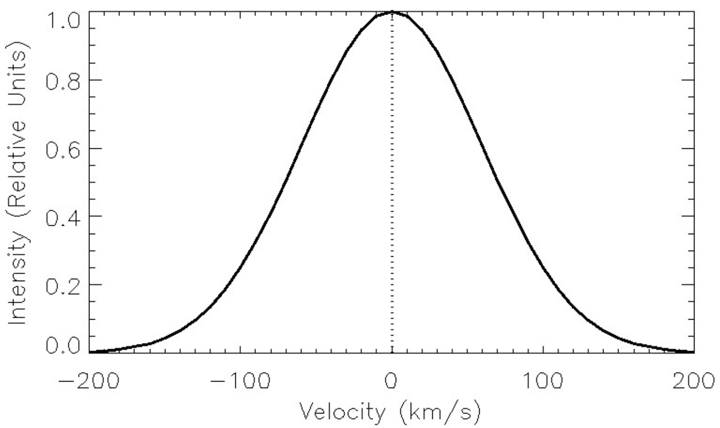


Assign each IS a color and combine information into a single image.

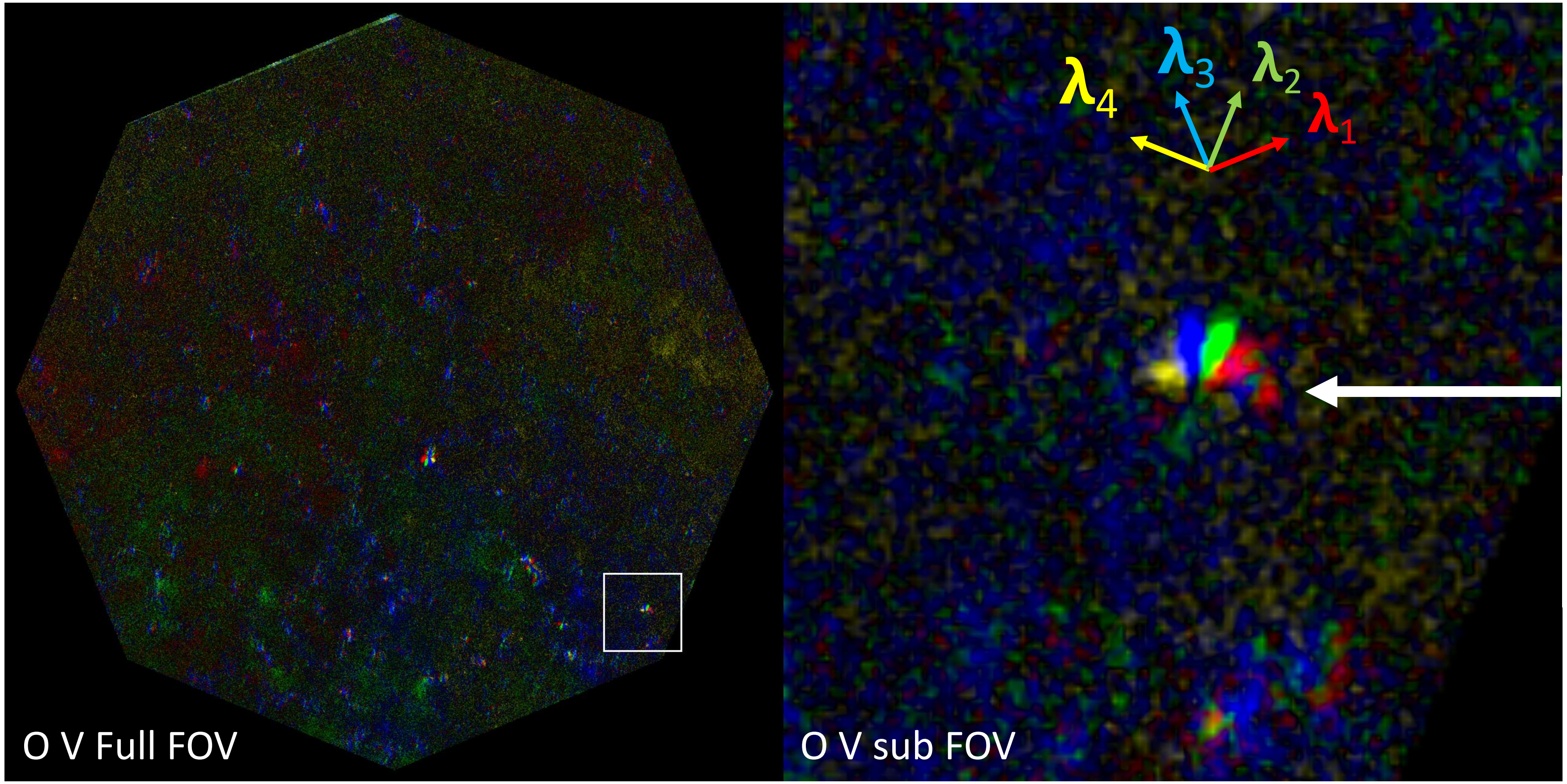
ESIS Color Images – All channels



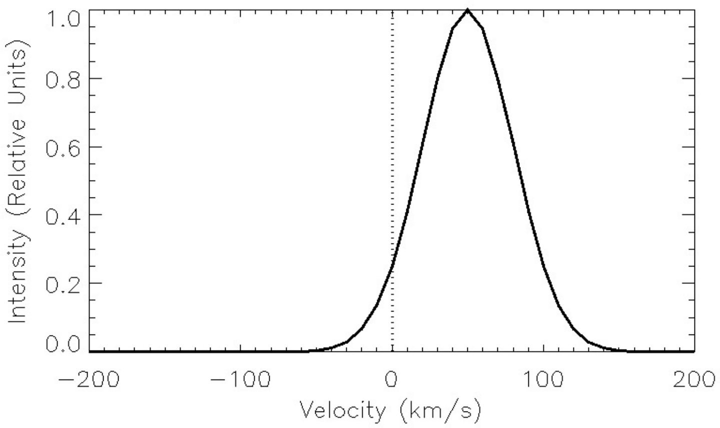
Broad, symmetric spectral line profile



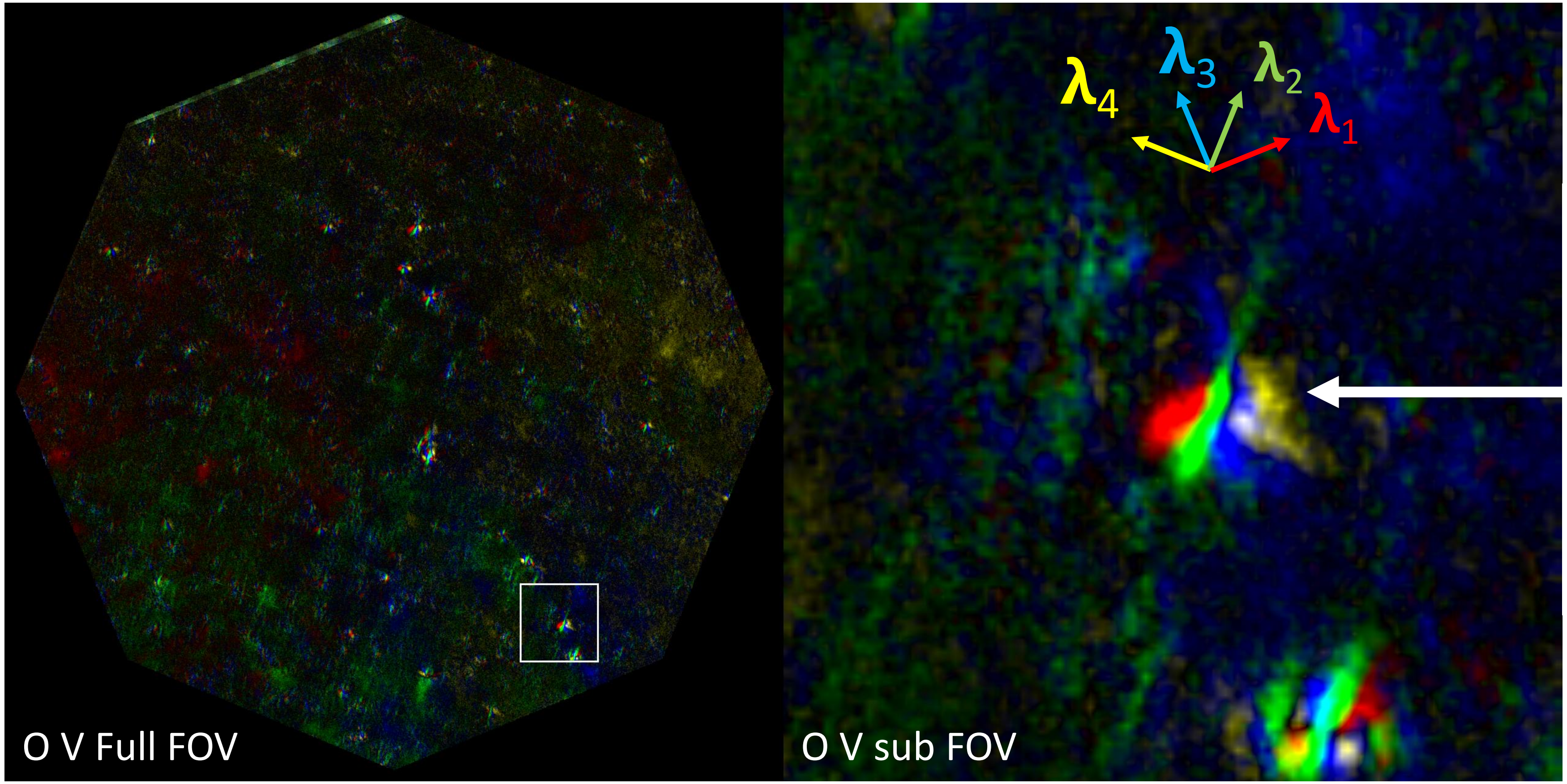
ESIS Color Images – All channels



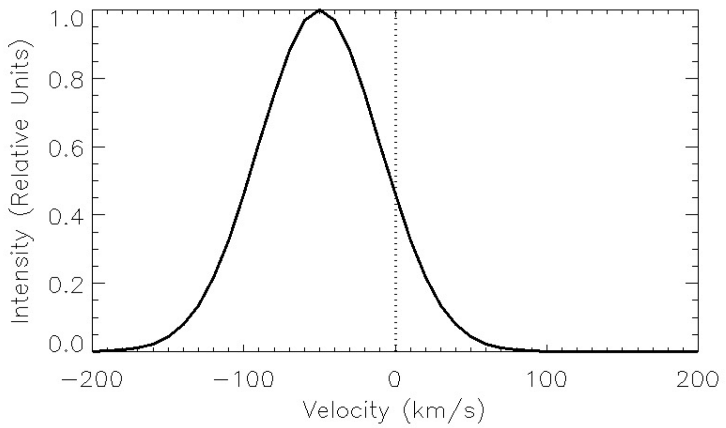
Red-shifted spectral line profile



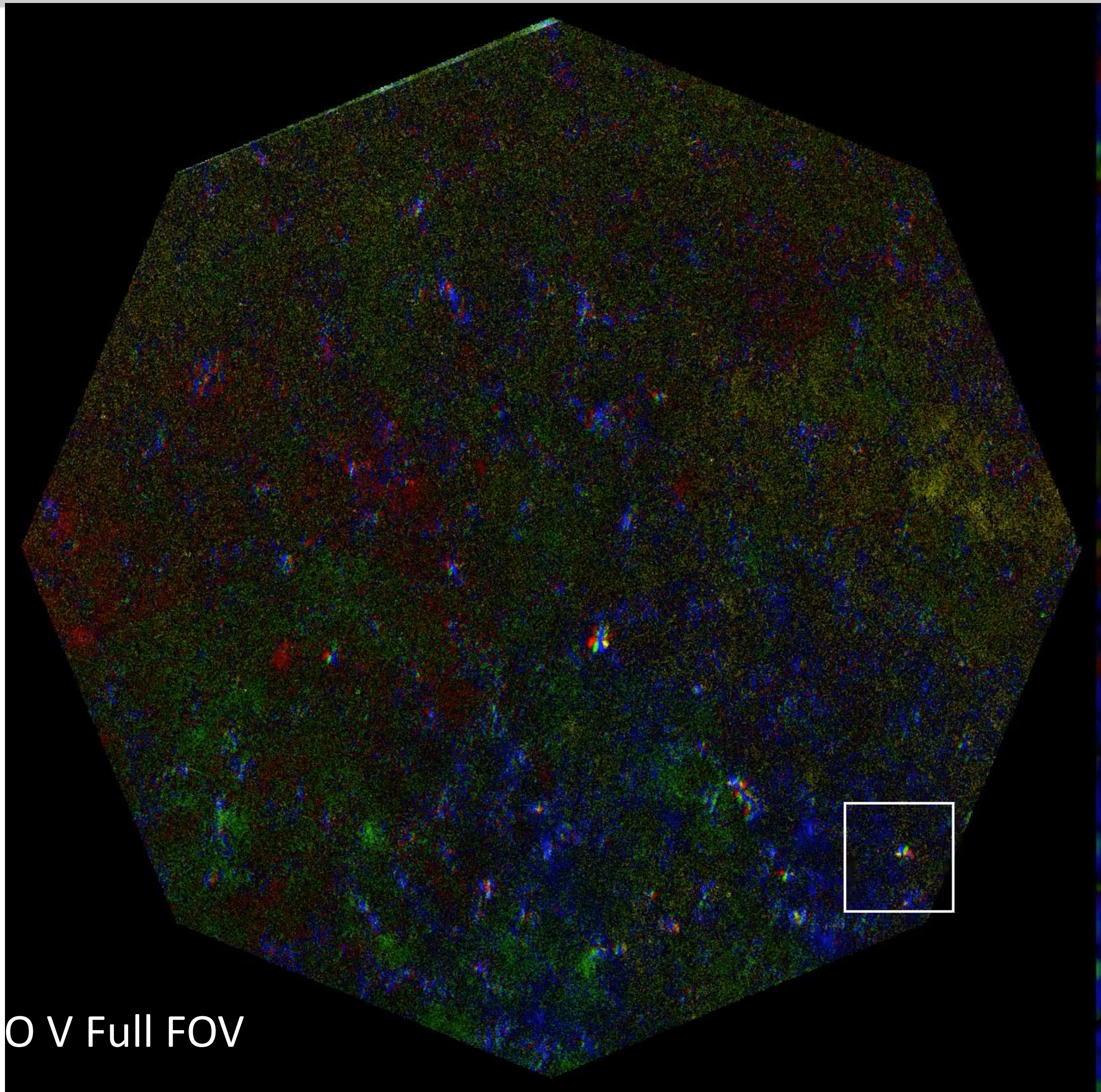
ESIS Color Images – All channels

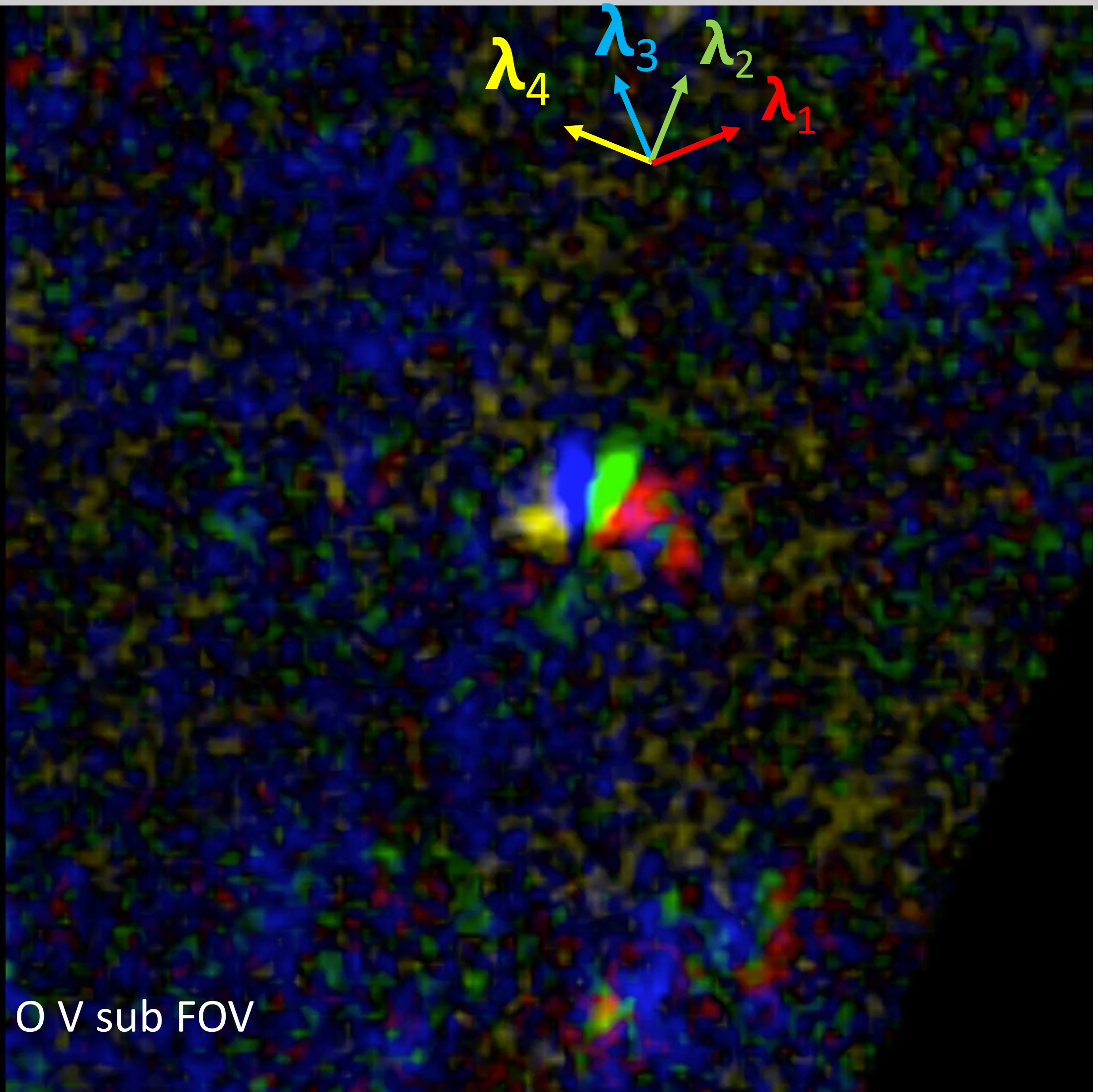


Blue-shifted spectral line profile

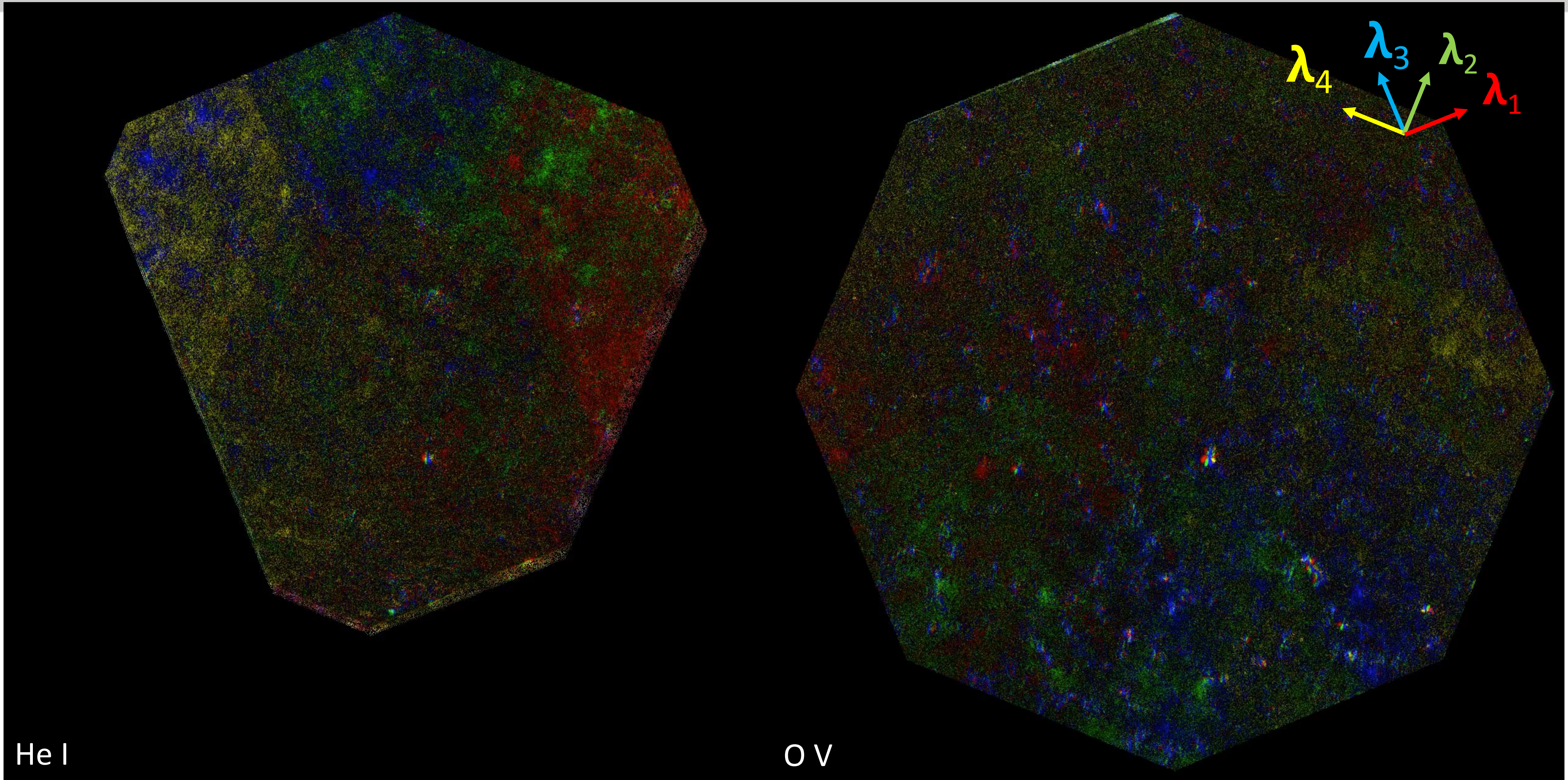


ESIS Color Images – All channels





Doesn't ESIS observe multiple spectral lines?



Multiple unfolding methods

Pursuing several inversion techniques in parallel:

- Brute force: Look up table for small, isolated events
- Tomographic methods : Multiplicative Algebraic Reconstruction Technique (MART)
- Supervised Machine Learning
  - Elasticnet from Python Scikit
  - Convolutional Neural Network (CNN)

Unfolding Velocity with Elasticnet

Write a set of linear equations:

Observations = Response Matrix # EM(space, velocity)

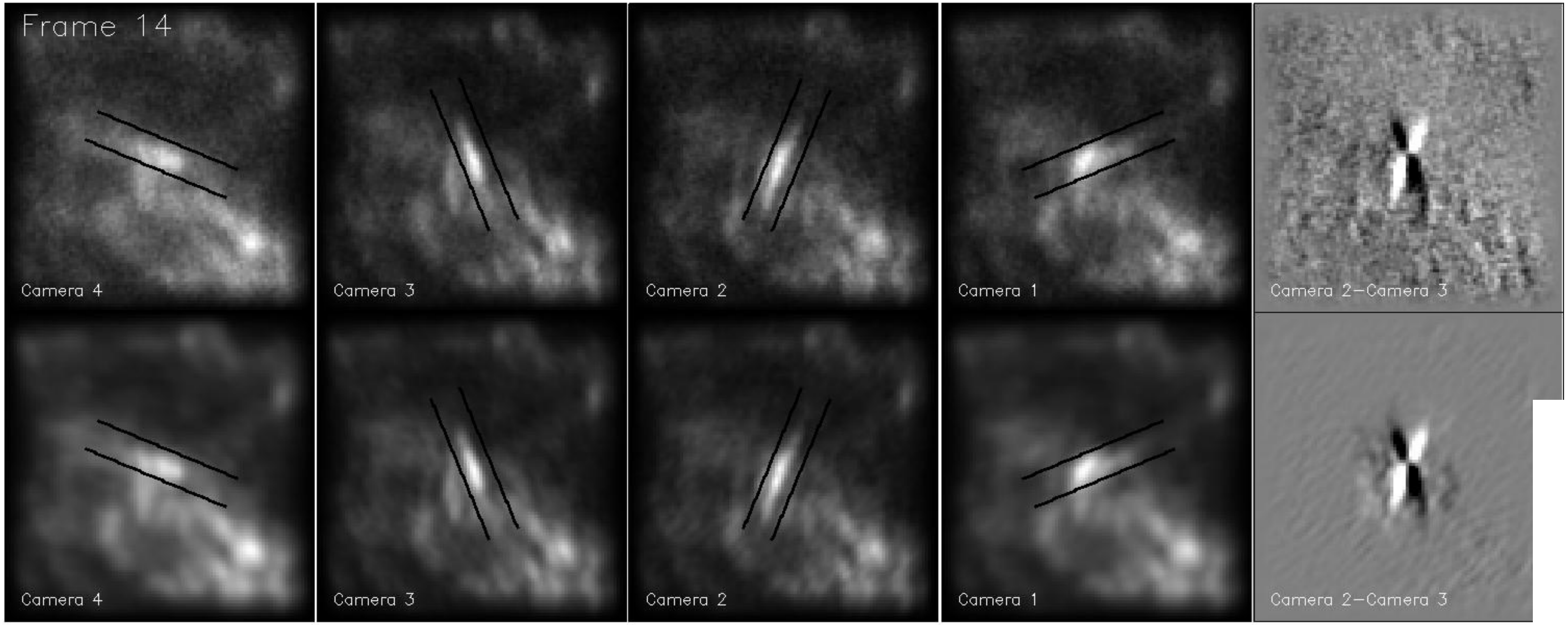
y = Mx

To find velocity, we find a ***sparse and smooth*** solution was best:

$$\boldsymbol{x}^{\#} = \operatorname{argmin}\left[\underbrace{||\boldsymbol{y_{obs}} - \boldsymbol{M}\boldsymbol{x}||_2^2}_{\text{Standard least squares term}} + \underbrace{\alpha\rho||\boldsymbol{x}||_1}_{\text{Penalty on total EM set by } \alpha\rho} + \underbrace{0.5\alpha(1-\rho)||\boldsymbol{x}||_2^2}_{\text{Penalty on square EM set by } 0.5\alpha(1-\rho)}\right]$$

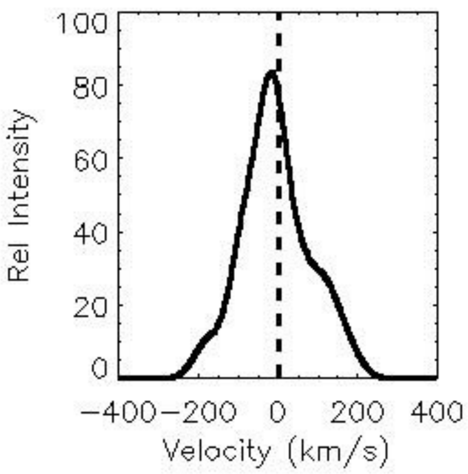
ρ = 1 -> sparse solution
ρ = 0 -> smooth solution

Preliminary results from Elasticnet



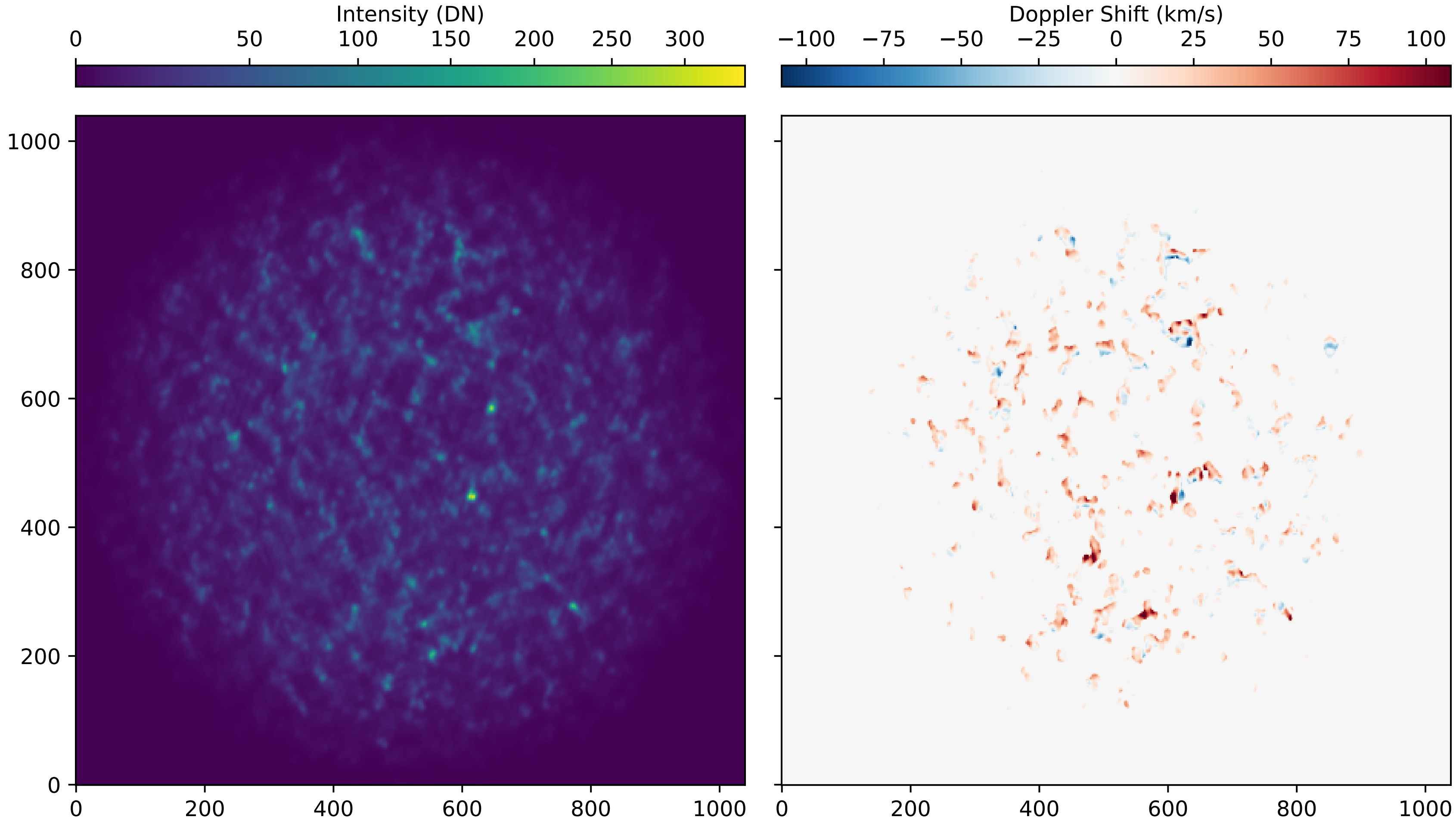
Observed data

Data calculated from inversion



Line profile of event

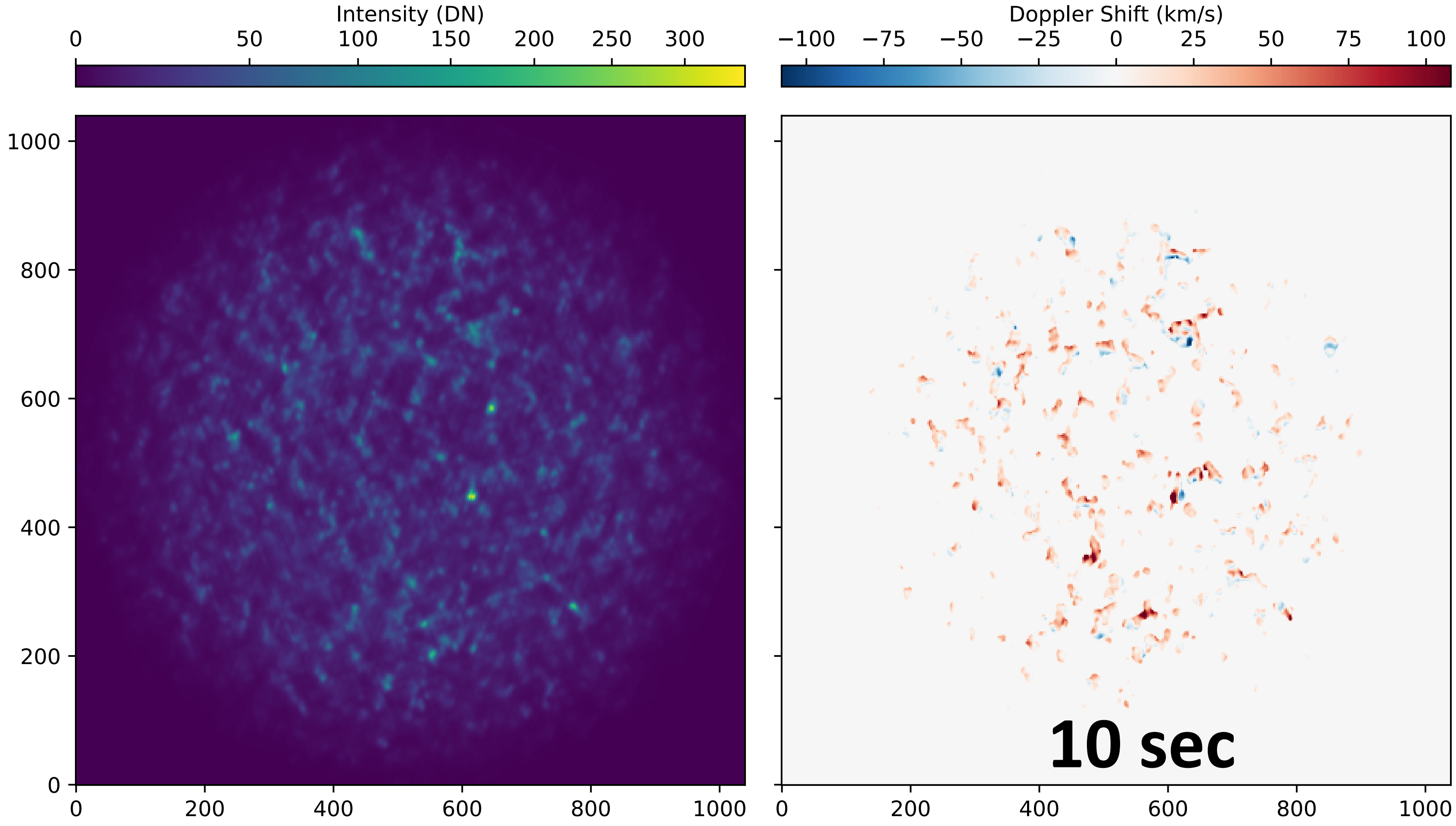
Preliminary results from MART

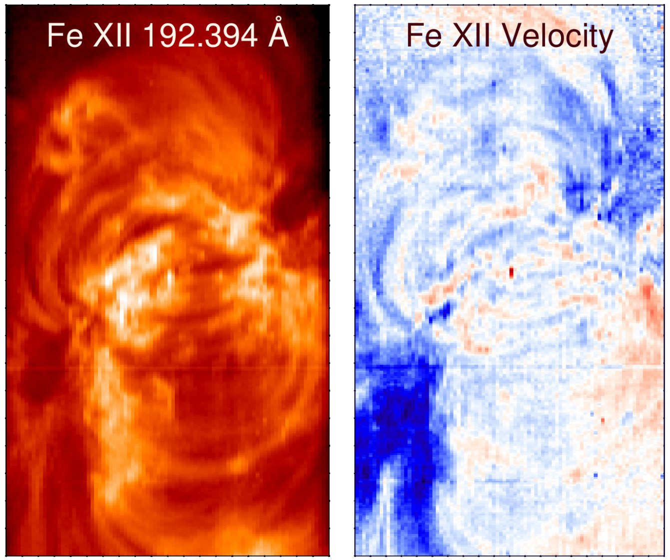


ESIS can generate moments of the line profile every 10 seconds

Images courtesy of Jake Parker, Roy Smart, Charles Kankelborg (MSU)

ESIS vs EIS





2 hours

Images courtesy of Jake Parker, Roy Smart, Charles Kankelborg (MSU)

Summary

Primary Measurement Target	Conclusions
Full Sun density, abundance, and temperature (COSIE, MOXSI)	Imaging spectrometers are revolutionary. Offer diagnostics not available by any other means. Inversion methods are essentially solved.
Velocity (ESIS)	CTIS with multiple angles is greatly simplifies the inversion. Inversion methods are still under development. Multi-slit spectrometers offer an alternative.

What’s next?

Imaging spectrometer data allows for rapid measurement of temperature, density, abundances, and velocities over large FOV.

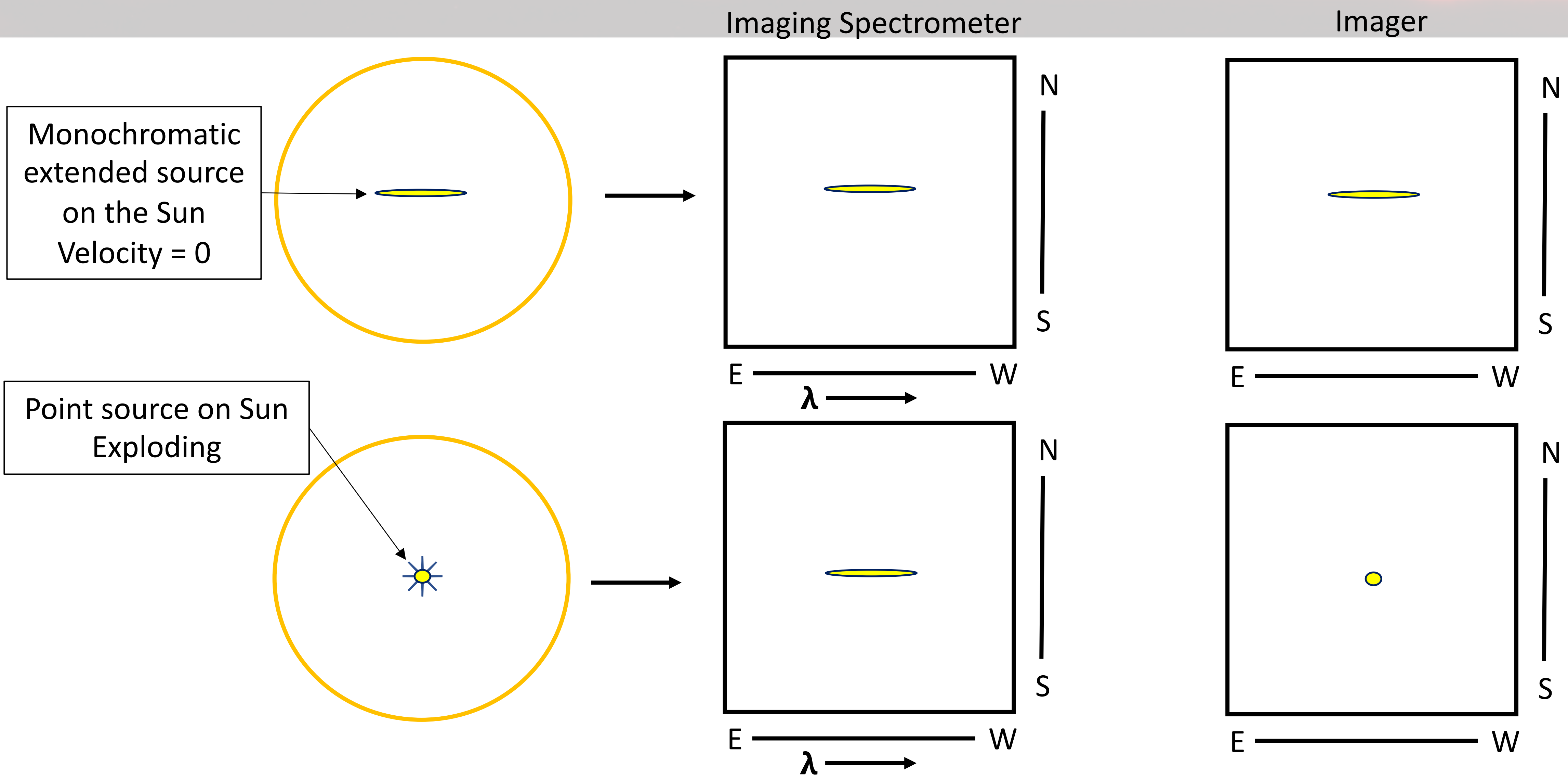
Inversion techniques can be applied to similar observations of extended astrophysical objects.

These diagnostics can be used to solve many open solar physics questions, develop space weather models and forecasting capabilities, and probe fundamental physics in the universe. ***These key capabilities are currently missing from the Heliophysics System Observatory.***

BACKUP

Why not add an imager?

Imagers help distinguish between spatial/spectral signatures in single point sources.



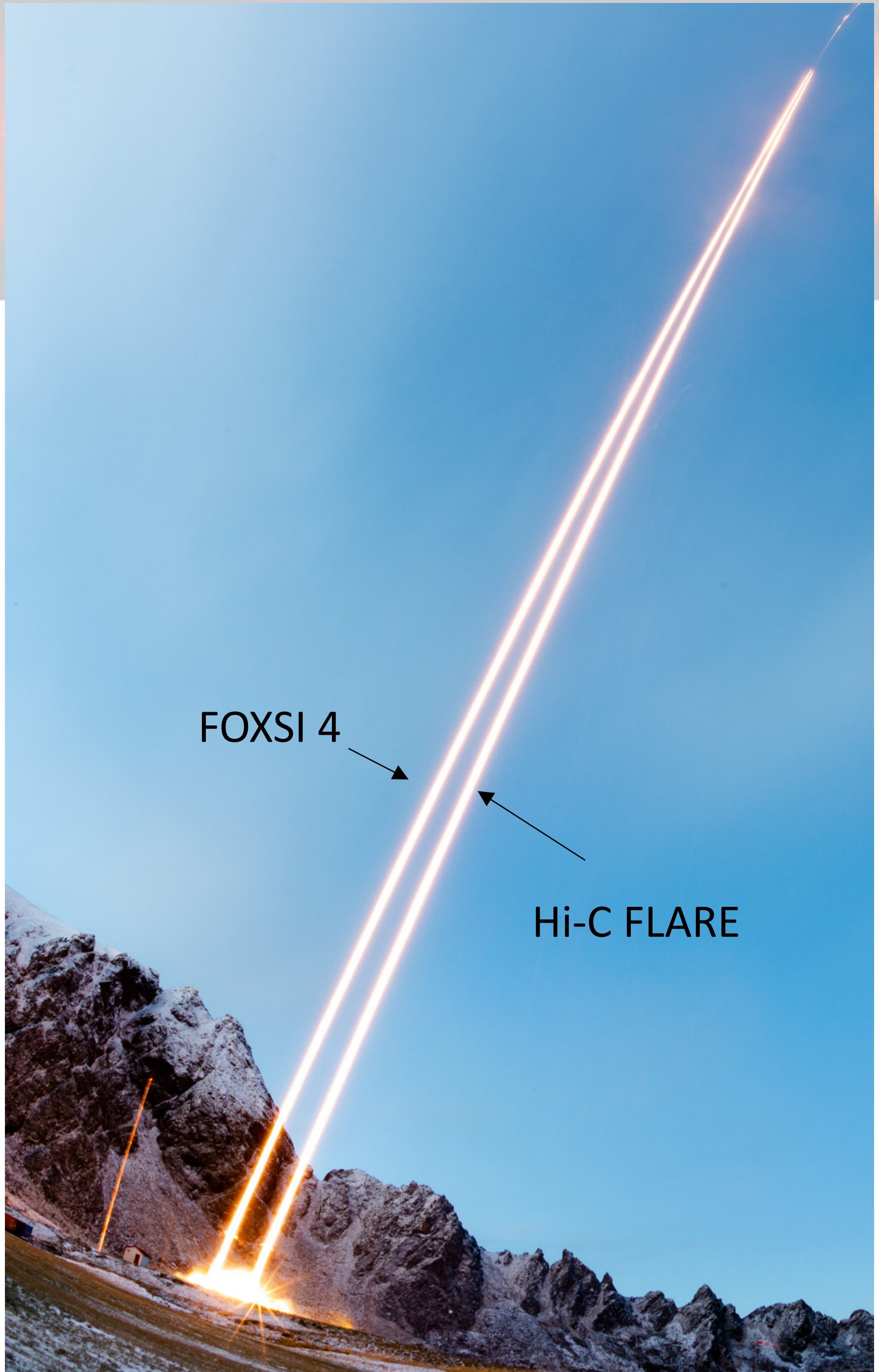
4 Imaging Spectrographs in Development

Name	Science Targets	Primary Measurement Target	Field of View	Wavelength range	Platform
MOXSI (A. Caspi, SwRI)	Flares and AR Heating	Temperature and abundance	Full Sun	0.1-4.0 nm (many coronal lines)	Cubesat (currently selected for Phase A study)
COSIE-S/ESS (L. Golub, SAO)	Space weather events and coronal evolution	Temperature and density	Full Sun	18.6 -20.3 nm (Fe XII/XIII density sensitive lines	Previously funded for tech dev, currently planned for SMEX/L5 mission
COOL-AID (A. Winebarger, MSFC)	Solar flare	Velocity of high temperature plasma	Partial Sun	12.9 nm (Fe XXI line)	Sounding rocket (funded for launch in 2024)
ESIS (C. Kankelborg, MSU)	Transition region explosive events	Velocity	Partial Sun (~600"field stop)	58 - 63 nm (He I and O V)	Sounding rocket (flew Sept 30, 2019)

Hi-C Flare Mission

Will be launched :

- During a solar flare (C5+)
- Simultaneously with FOXSI 4
- During the Parker Solar Probe close approach in March 2024
- From Poker Flat Research Range, Alaska

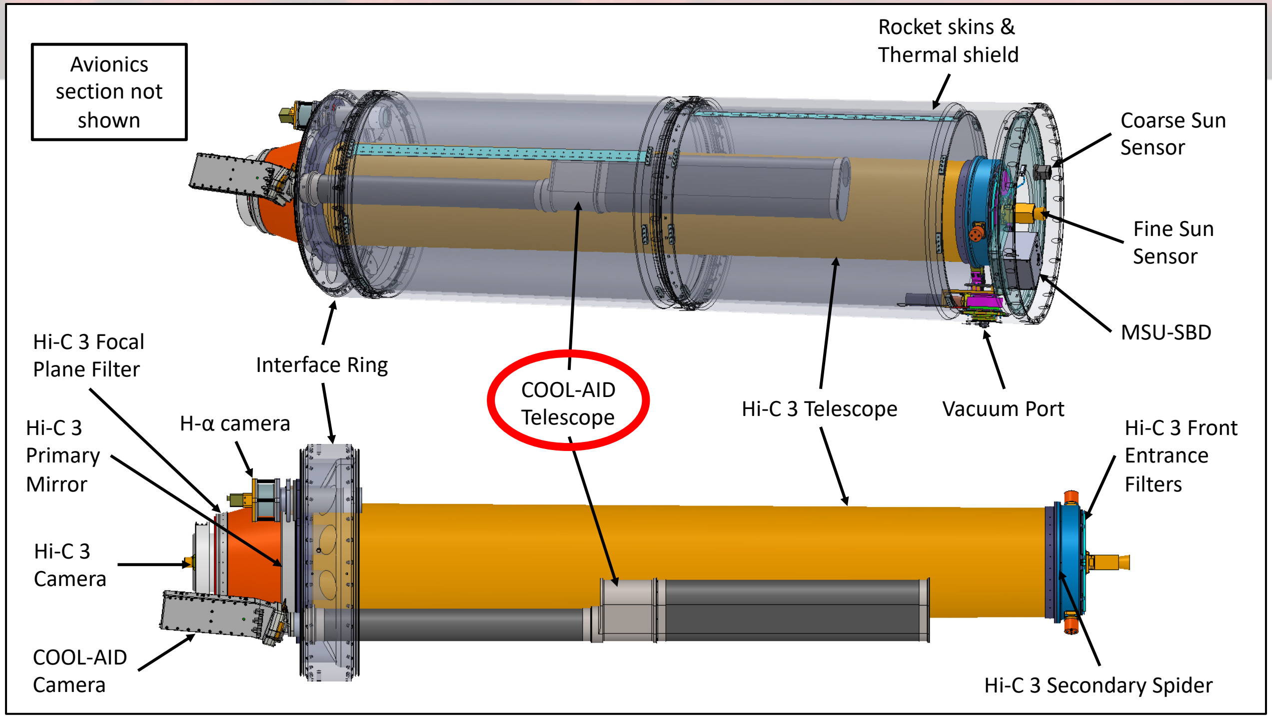


Images courtesy of the Sounding Rocket Project Office

Hi-C Flare Mission

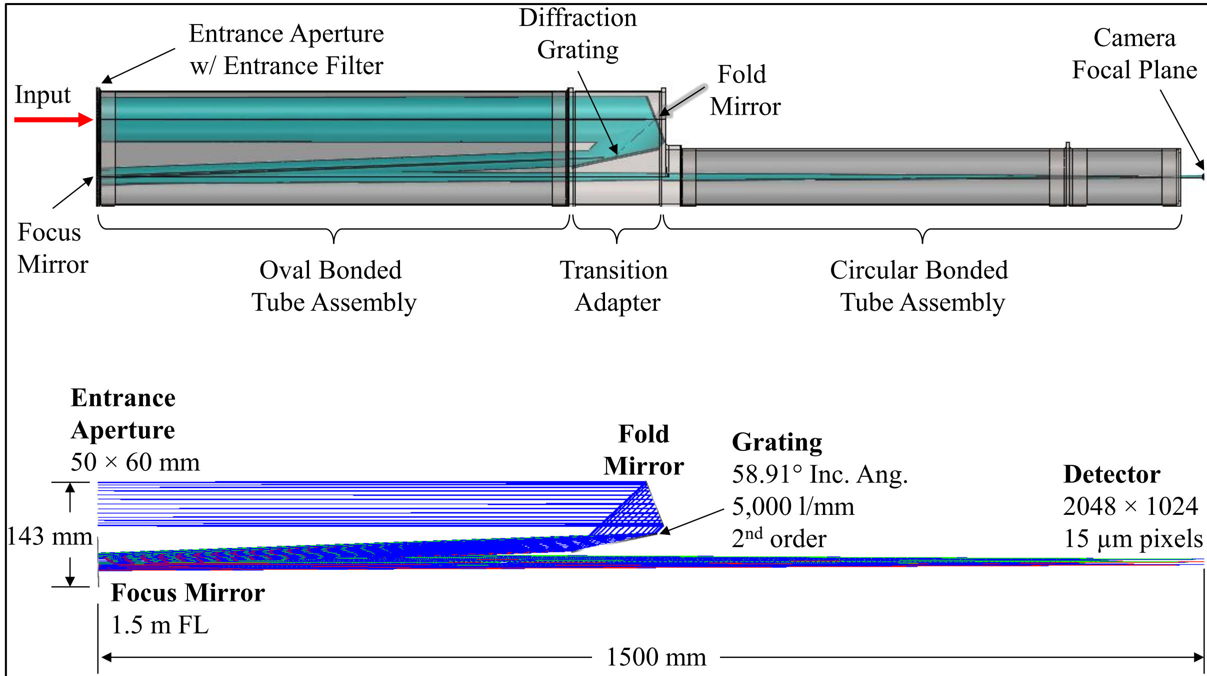
Hi-C 3 – High-resolution Coronal Imager

- High resolution (0.3”)
- High-cadence (1.2 s)
- New passband around the Fe XXI 12.9 nm spectral line formed at 11 MK



COOL-AID 1&2 - CTIS

- Targets Fe XXI 12.9 nm line
- High velocity resolution (< 10 km/s) and range (+- 1000 km/s)
- High cadence (1.5 s)
- Moderate spatial resolution (~ 2”)
- **Two COOL-AIDs with orthogonal dispersion directions (designed by Jenna Samra based on COSIE)**

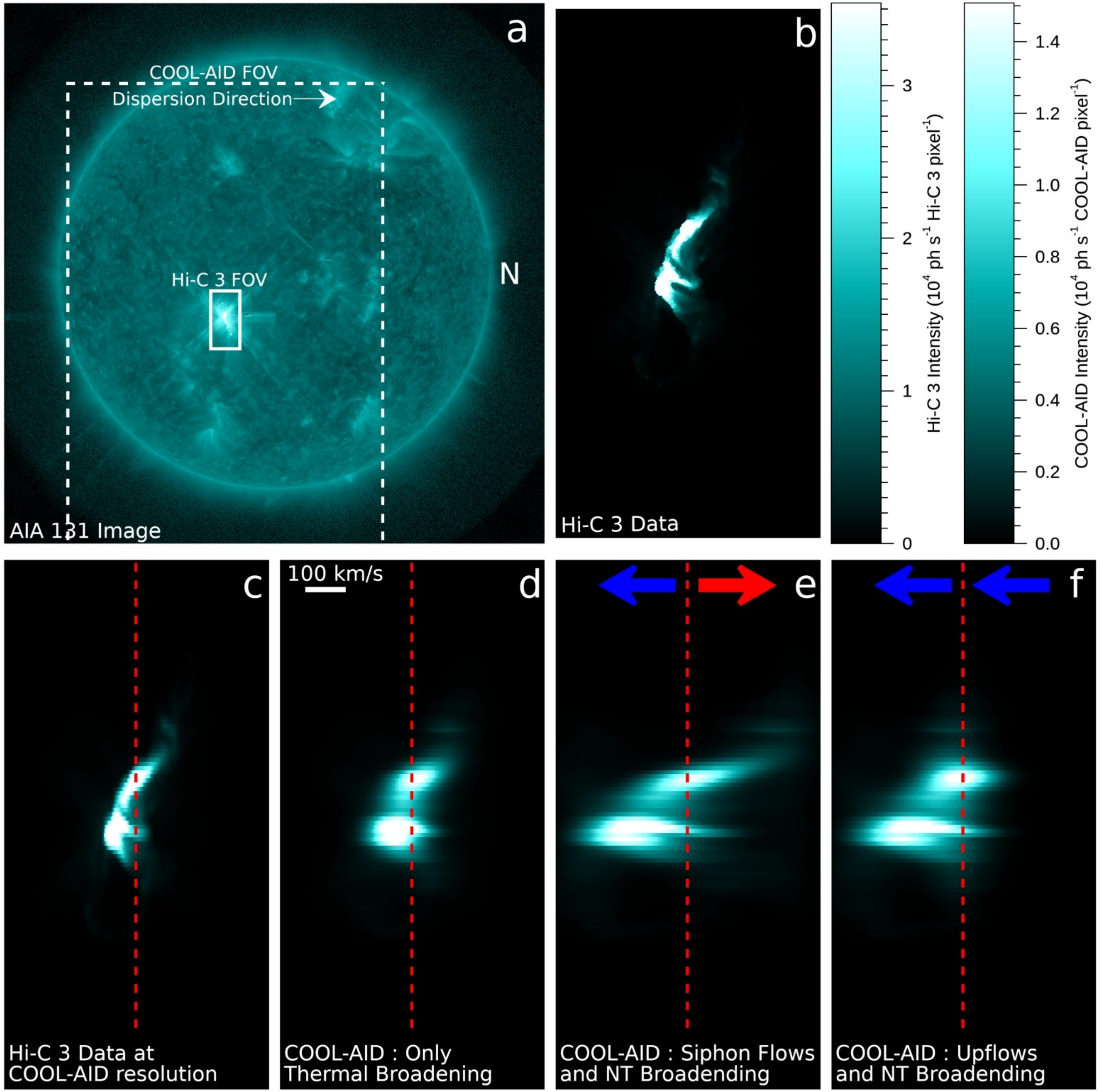


Montana State University – Student Built Detector

- Full-Sun X-ray detector
- Energy sensitivity similar to the low-energy passband of the GOES X-ray detector
- 1000 times the cadence

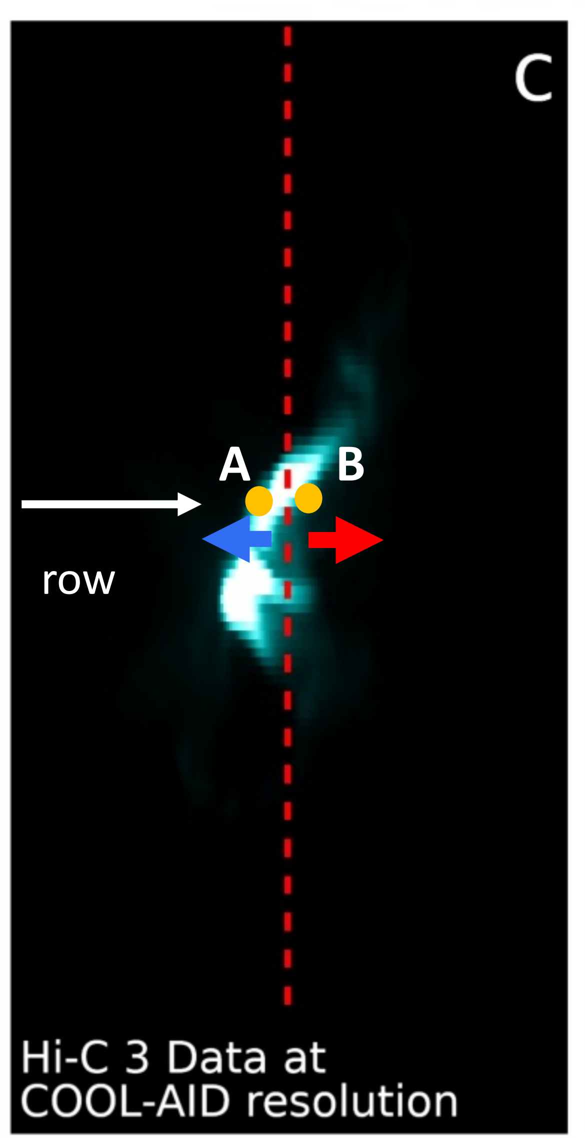
Predicting COOL-AID Data

COOL-AID is an instrument designed to measure velocities during a flare.



Does sparse inversion work for velocity?

Test case



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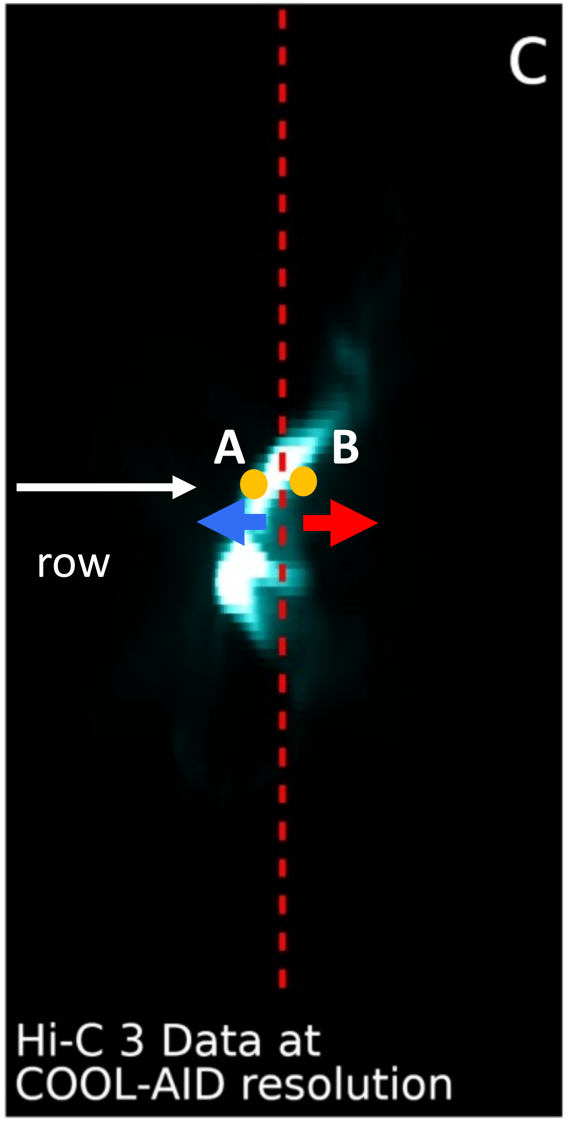

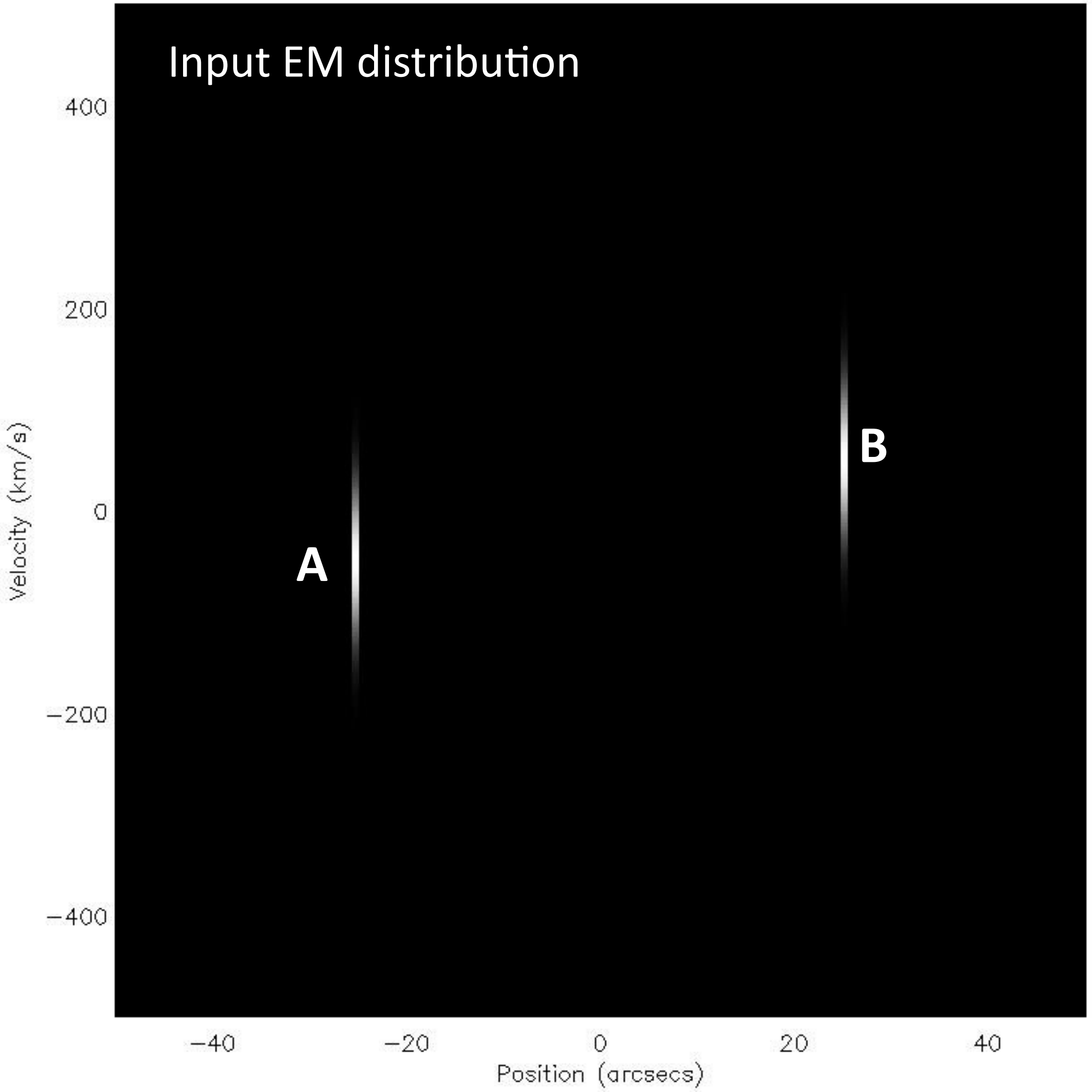

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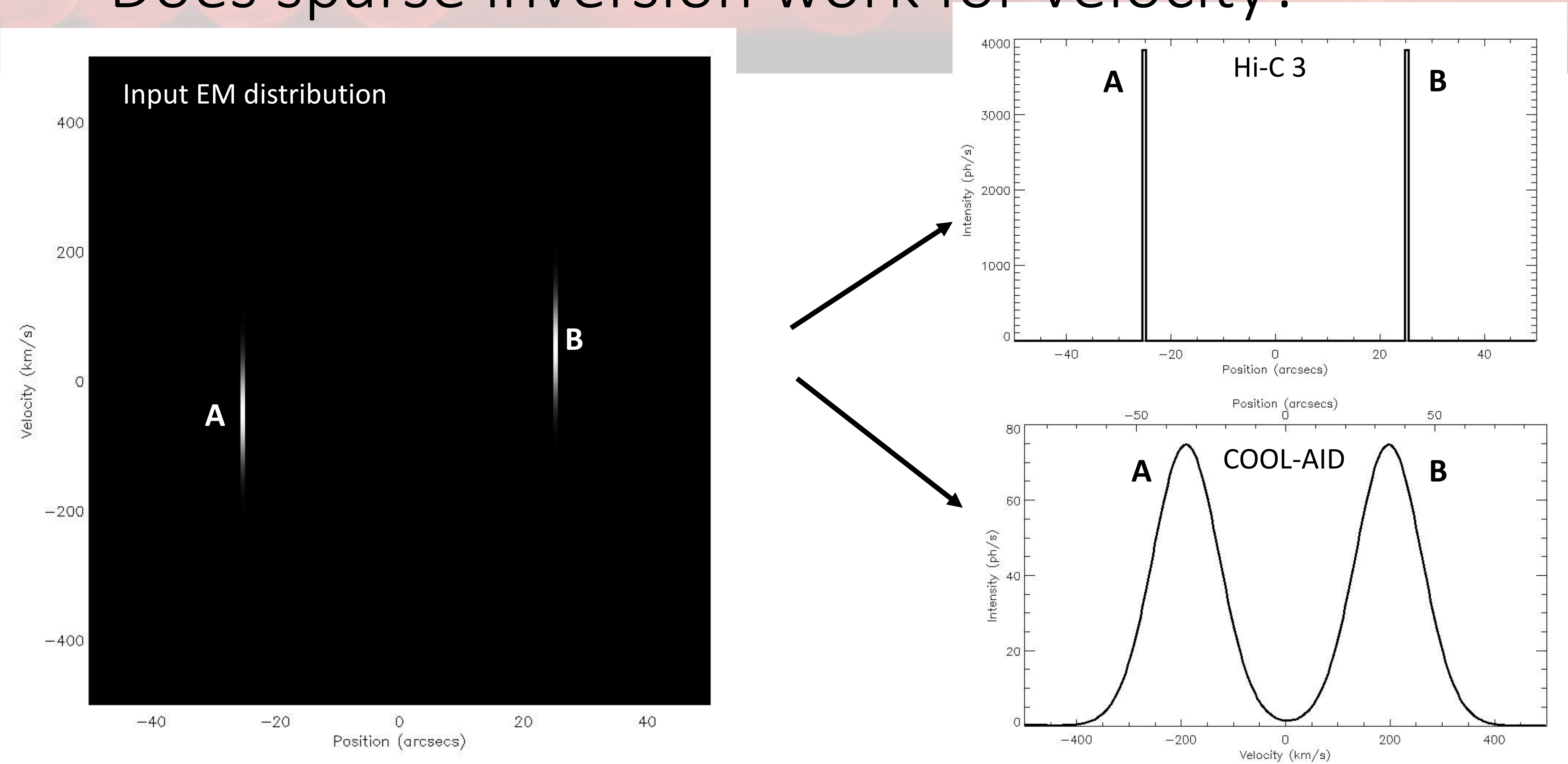
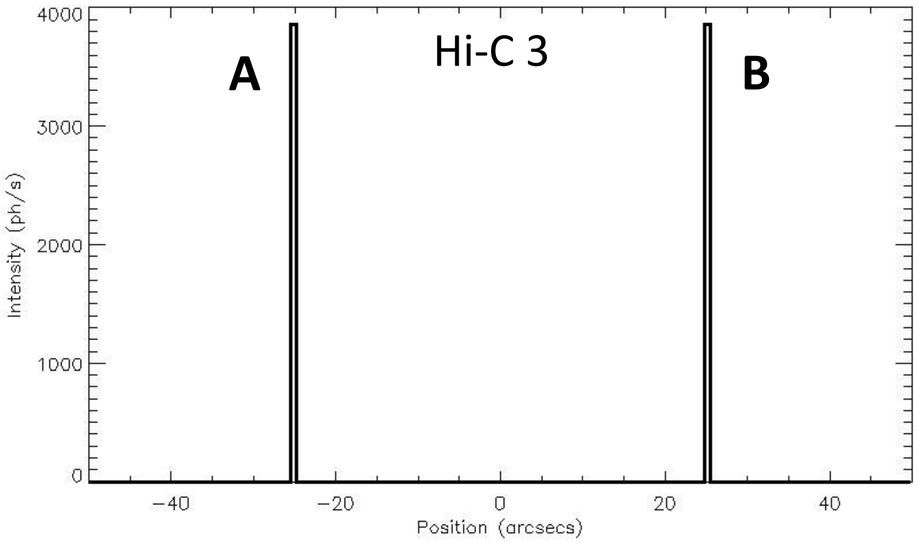
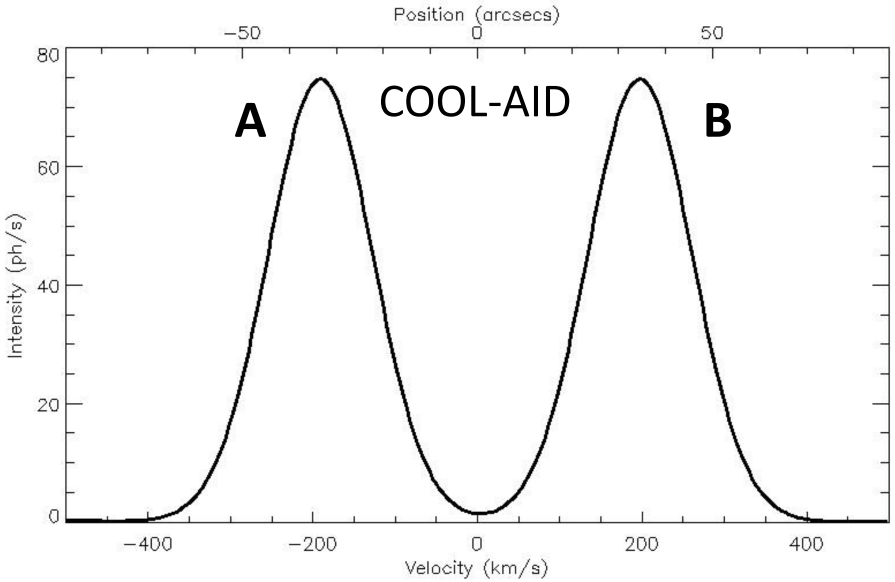
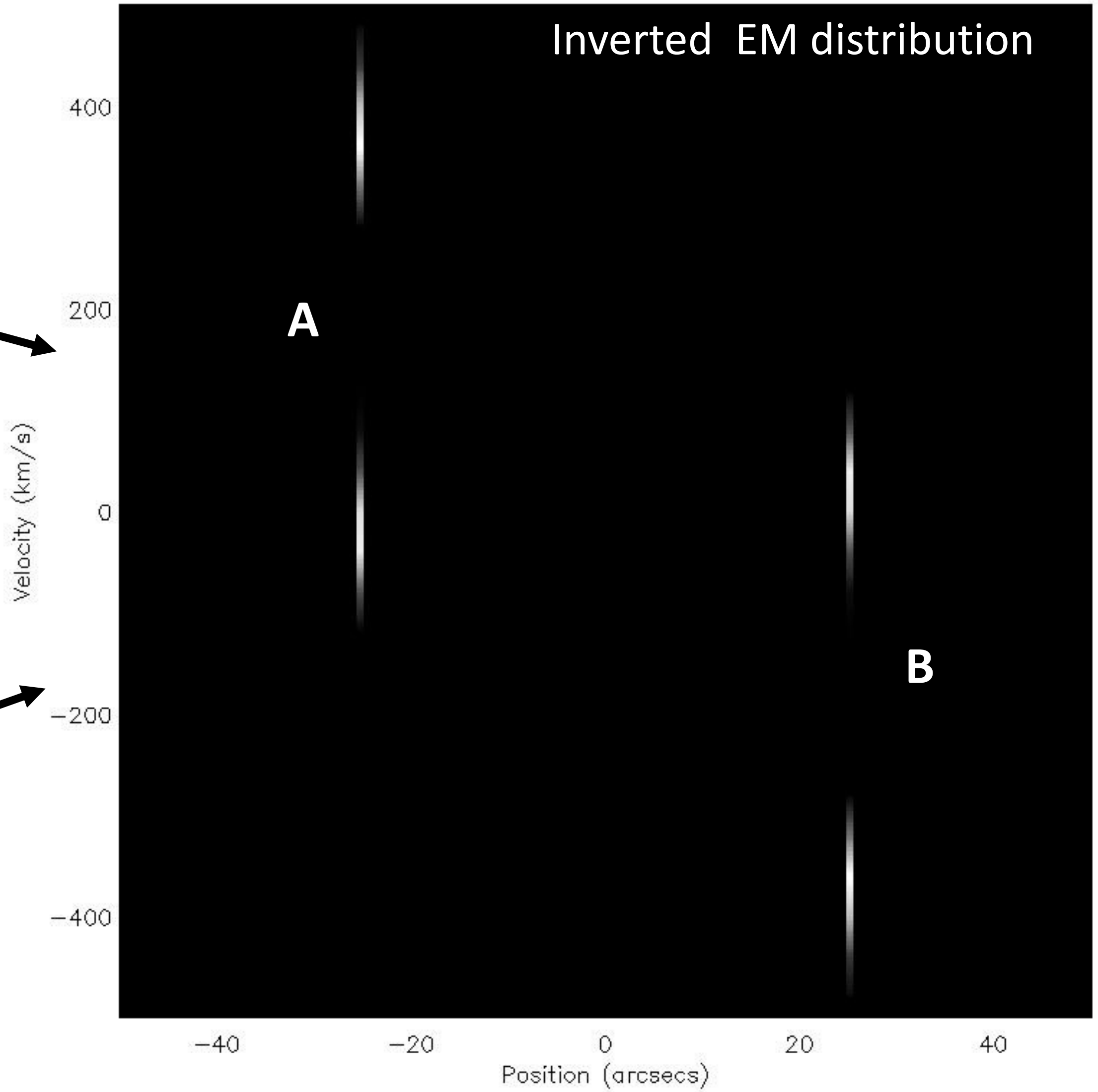


Inverting velocity is more complicated







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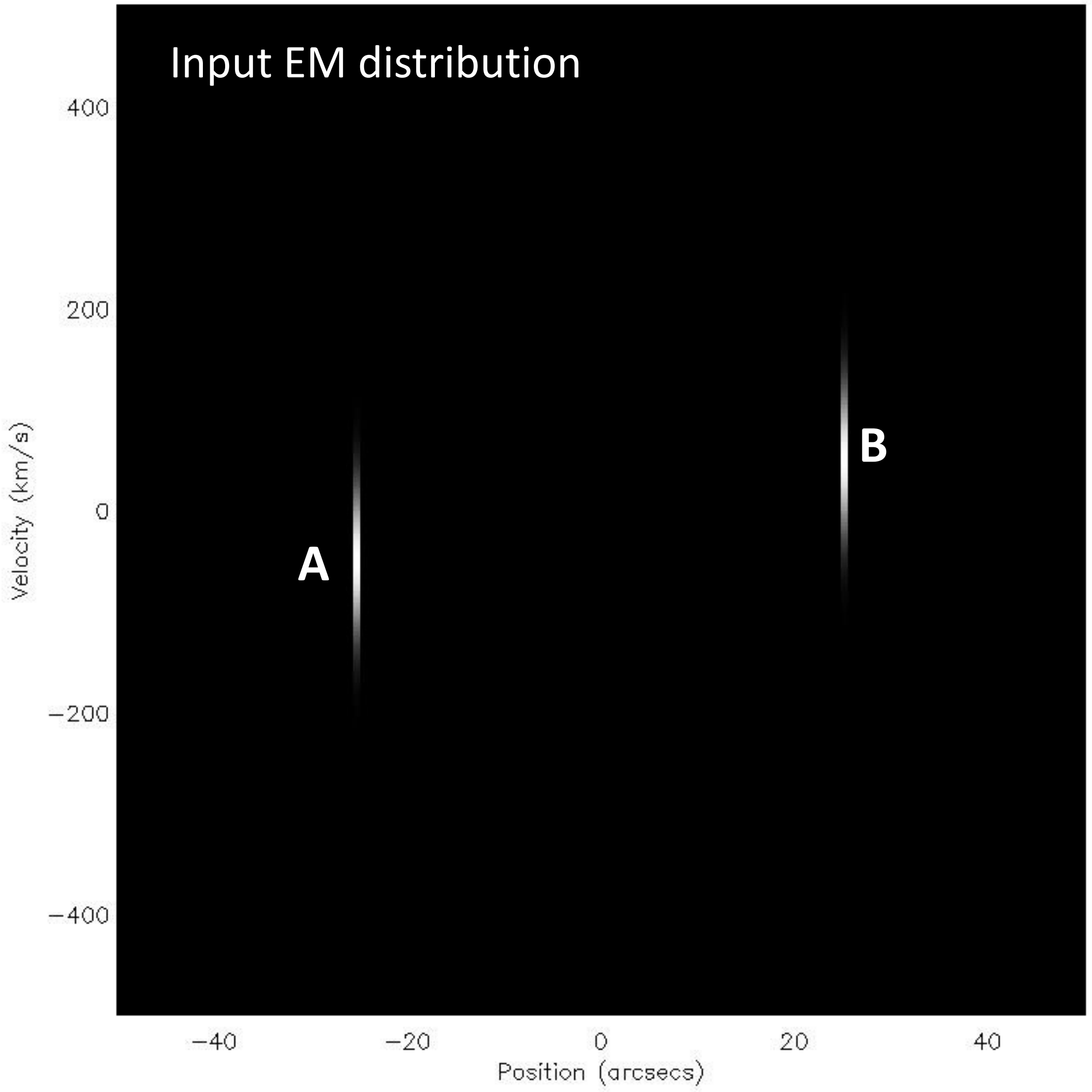
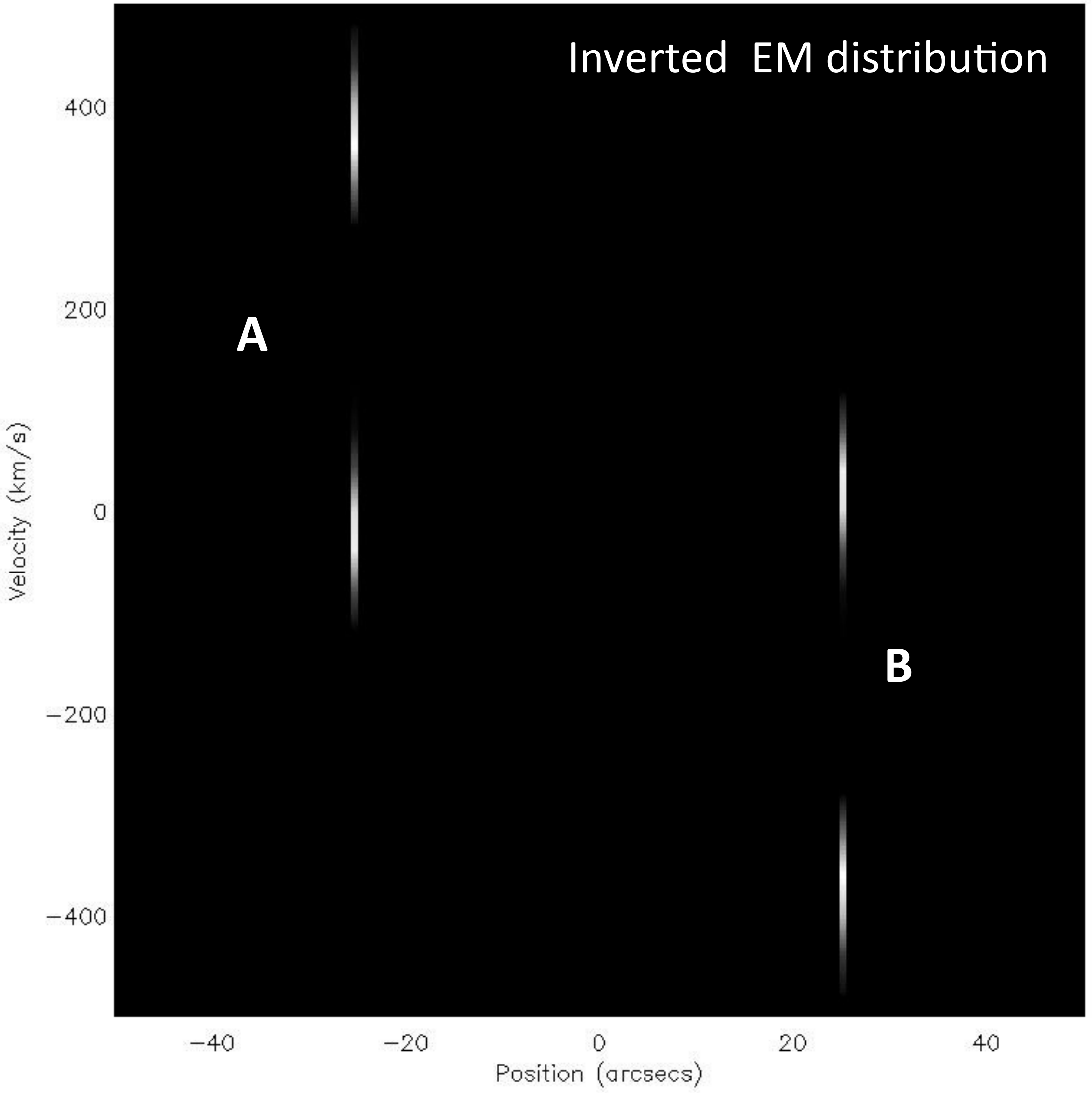
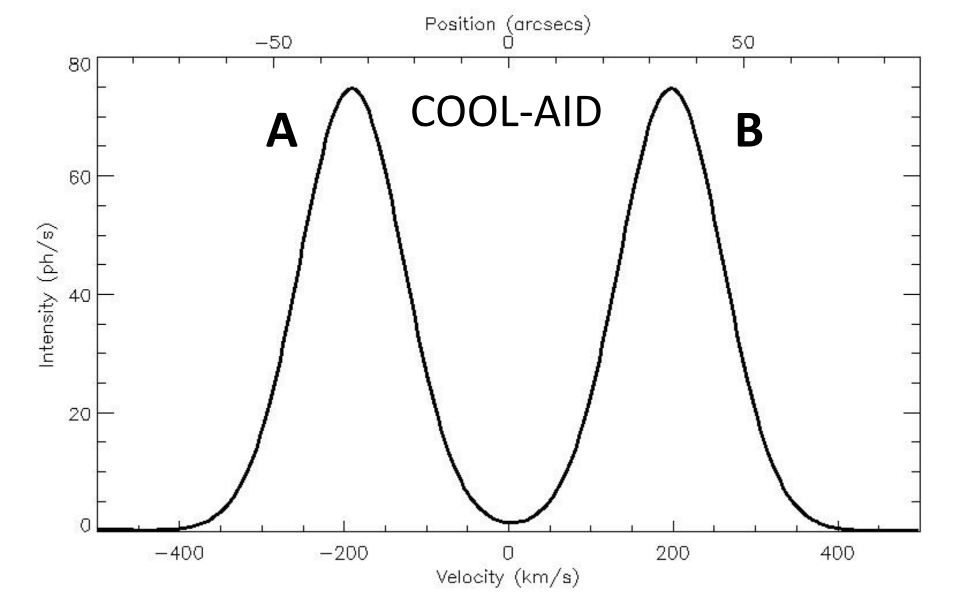




Where is COOL-AID signal coming from?



The inversion code does not know which spatial location the COOL-AID signal is coming from.

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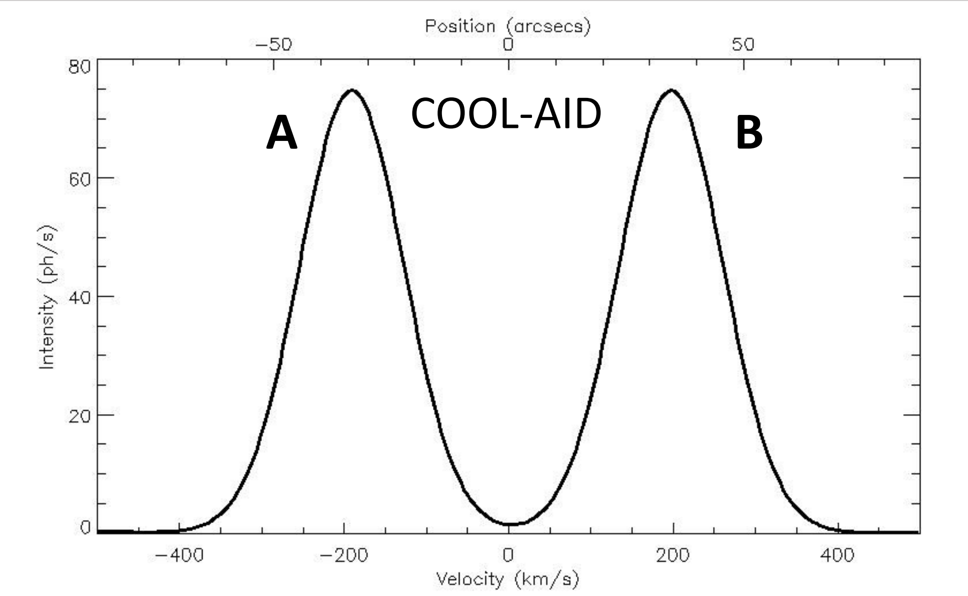

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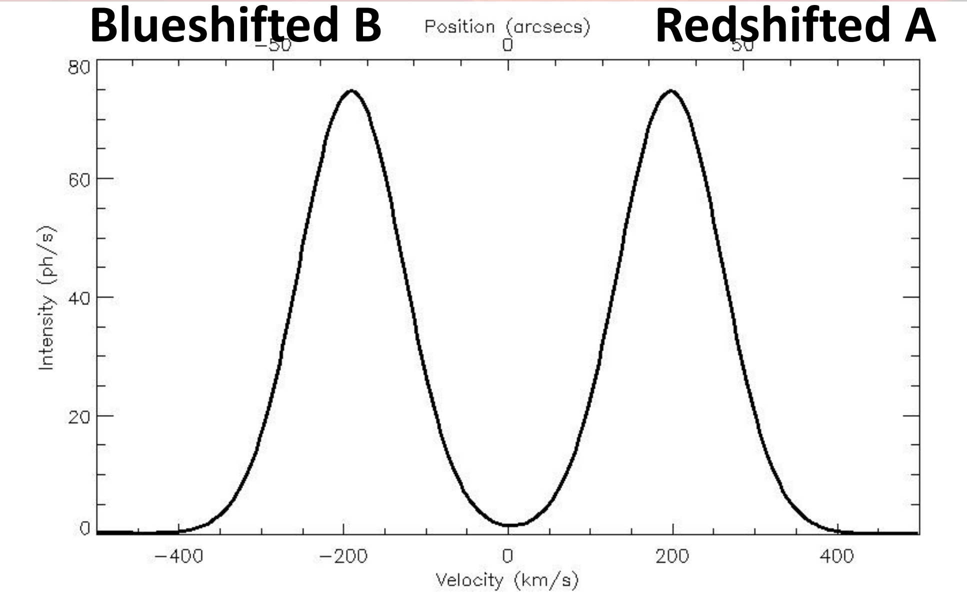

Just as likely…

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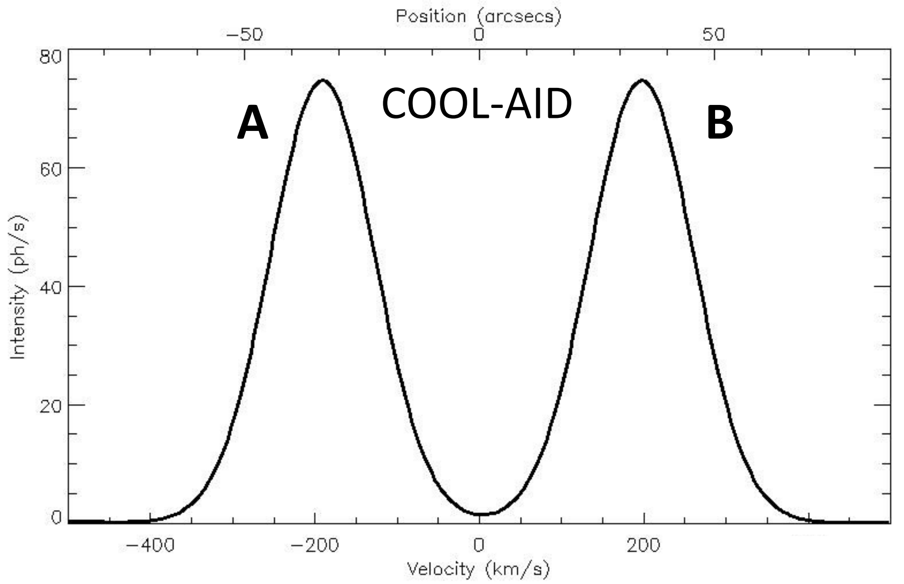

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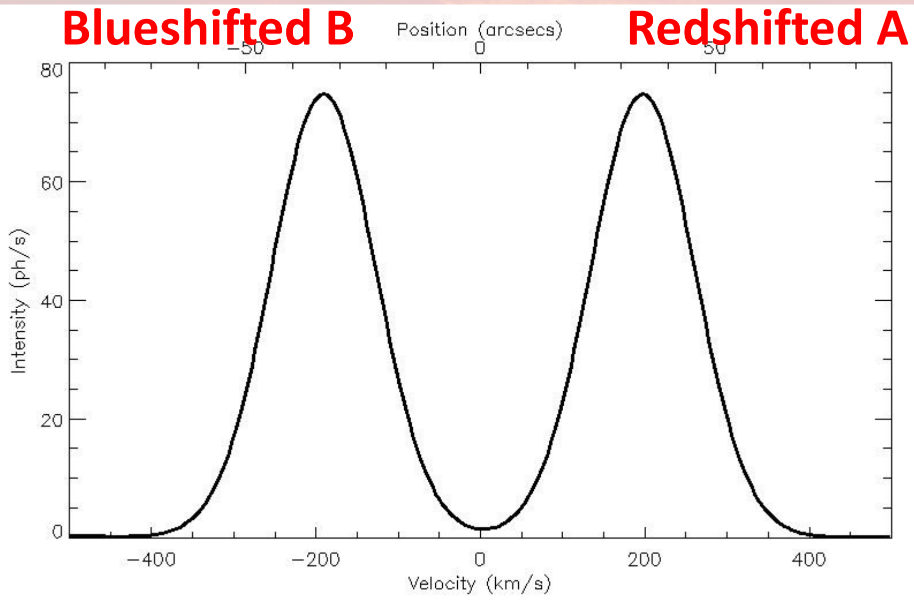
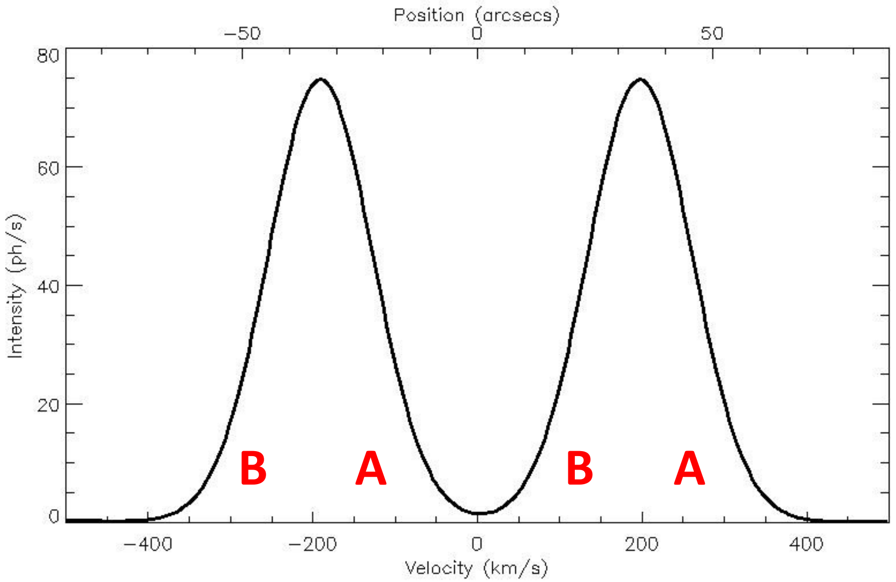


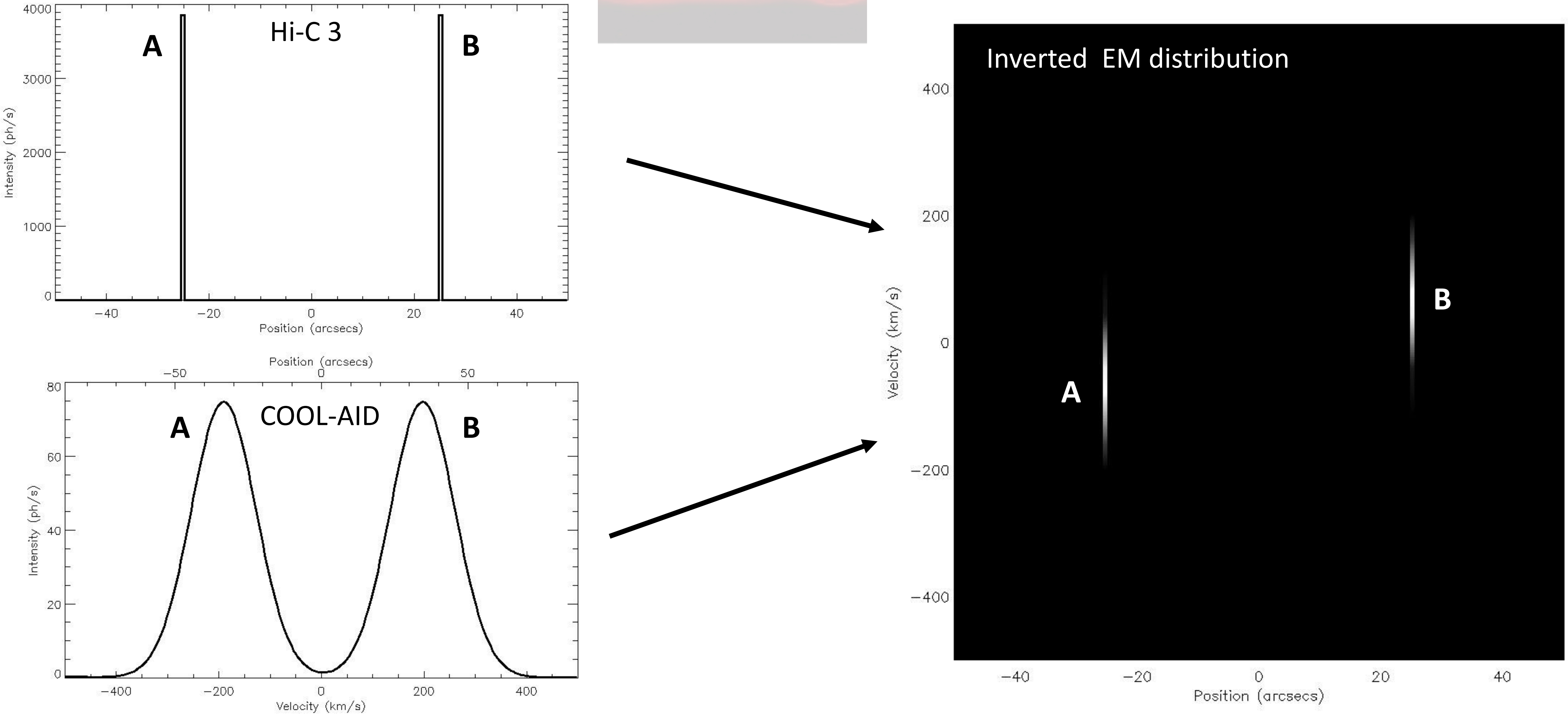
Just as likely…

Equally as likely…

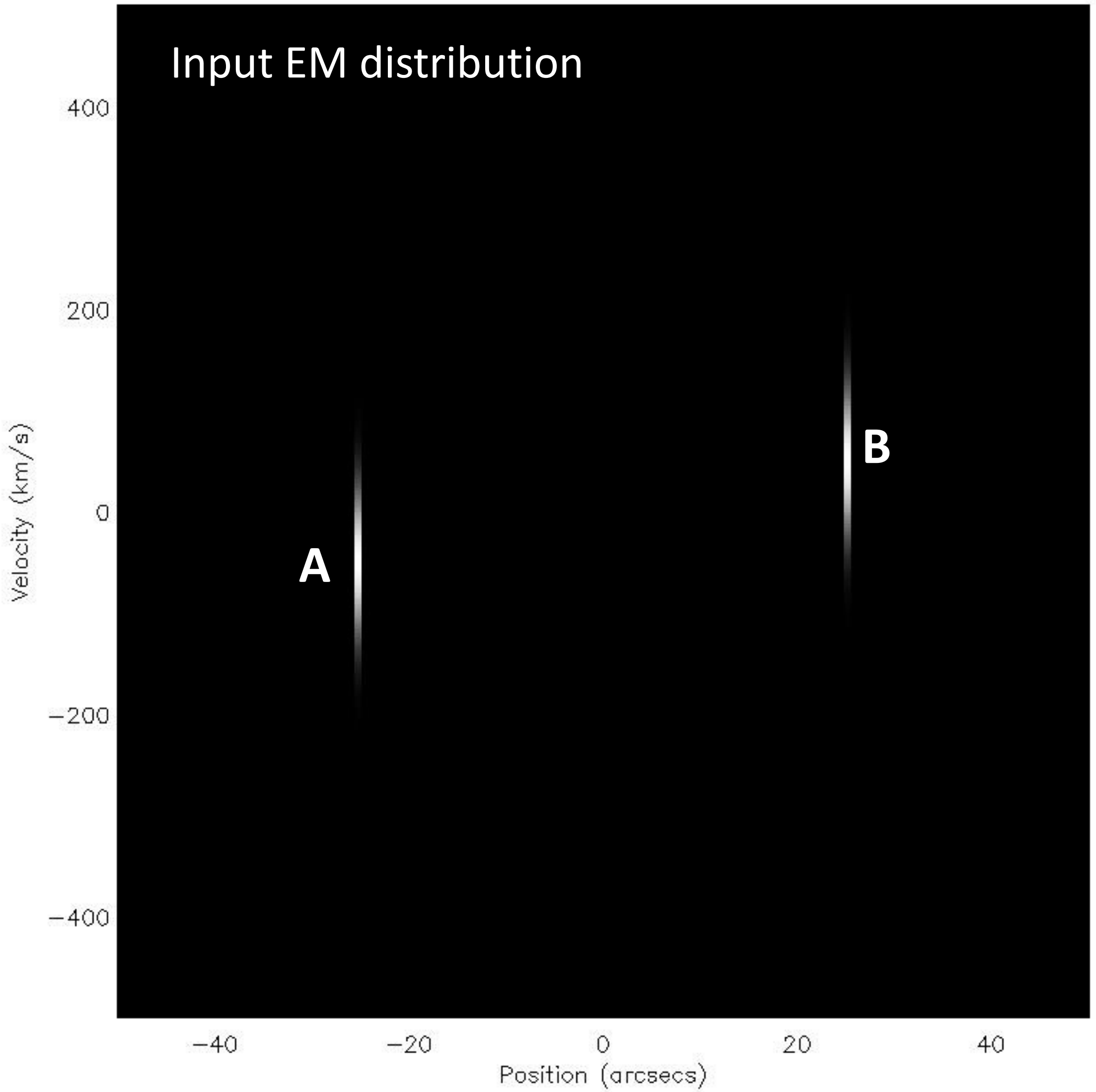


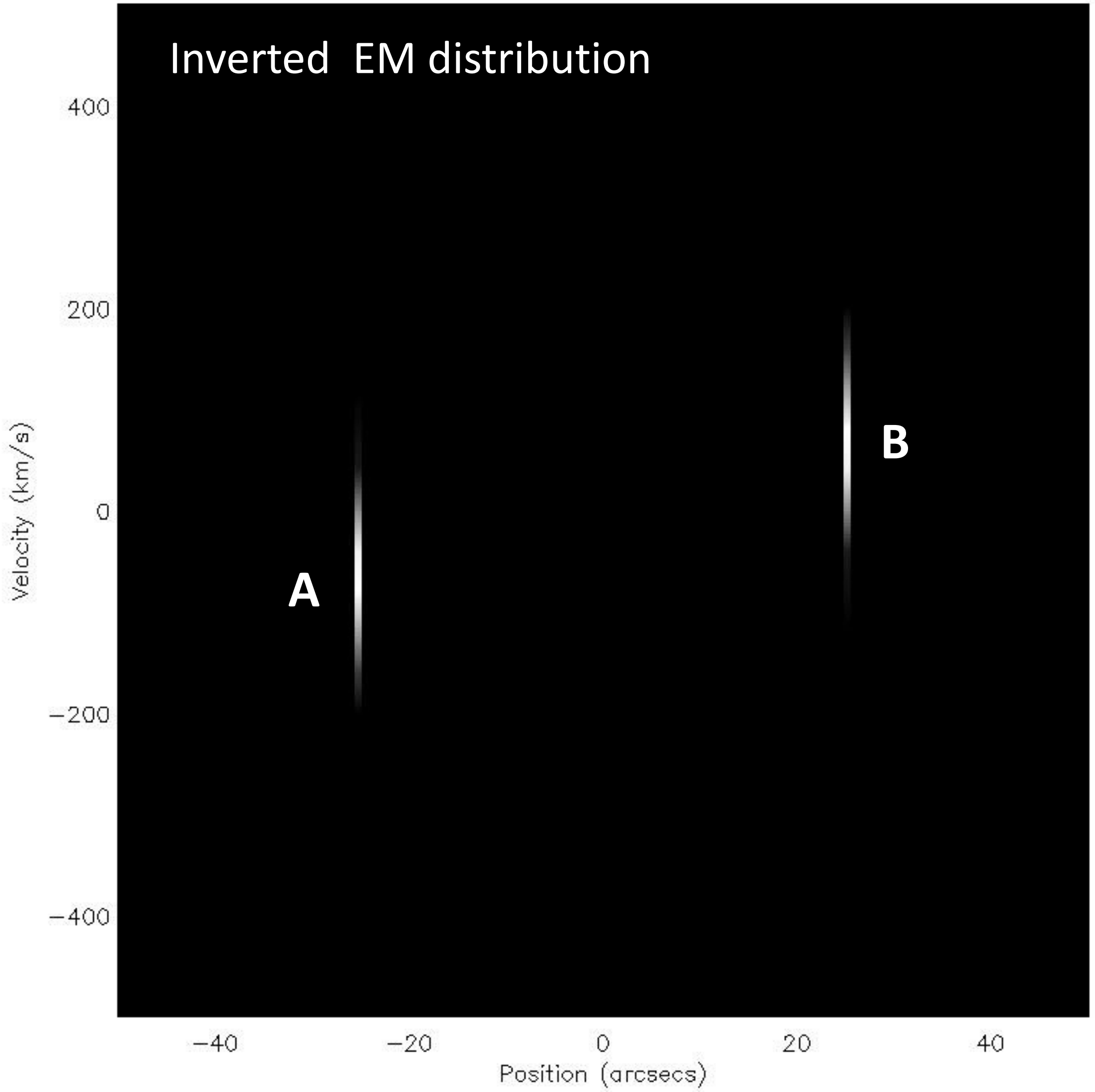
The returned solution assumes the COOL-AID signal is coming from a mixture of points A & B.

Inverting velocity is more complicated

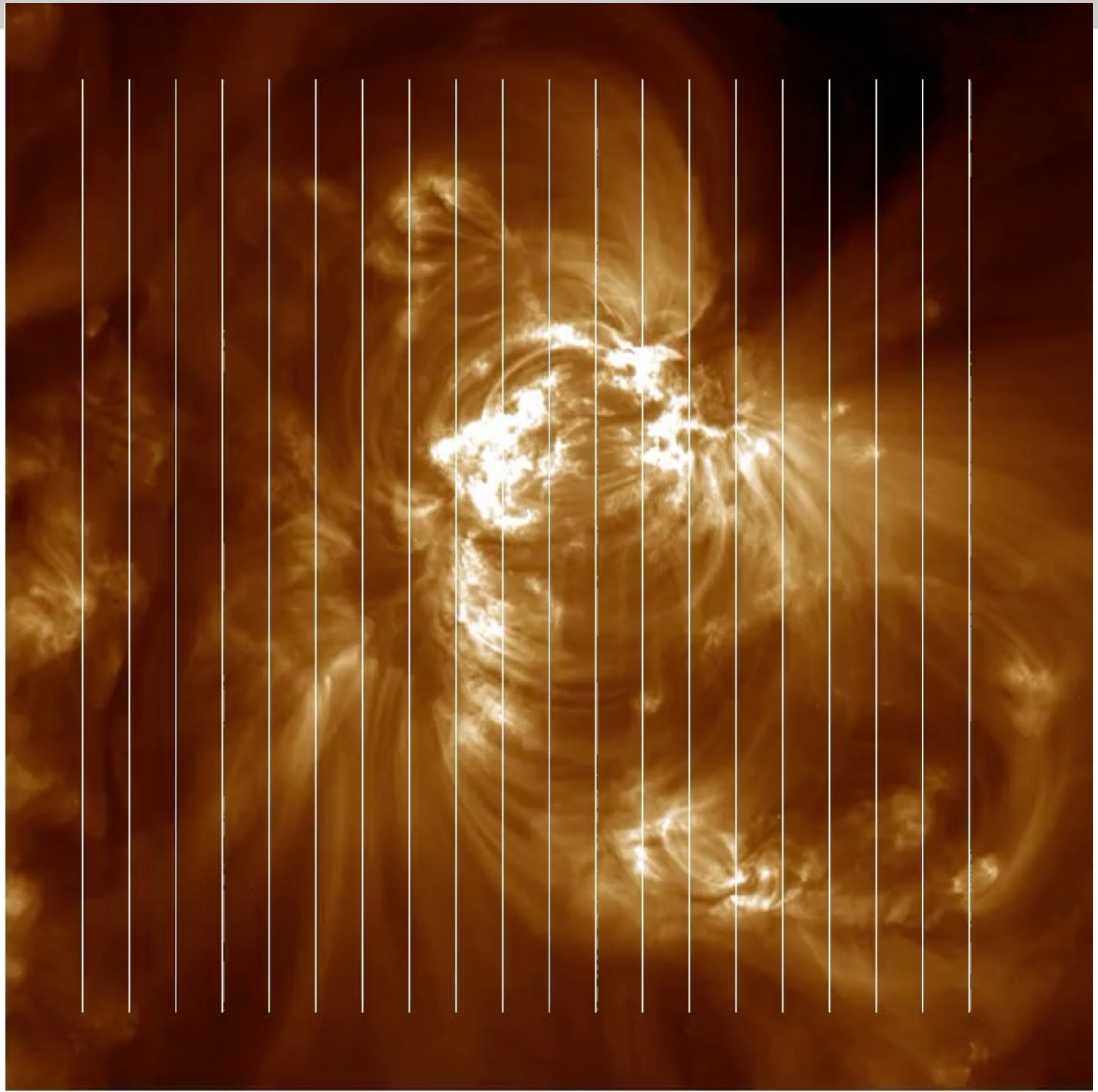


Inverting velocity is more complicated





Holy grail data set



Multiple-slit spectrograph

- Still requires scanning and careful selection of spectral lines
- Can create spatial/spectral confusion

Examples:

- Multi-slit Solar Explorer (MUSE, selected for a Phase A MidEx Concept Study)
- COROnal Spectropolarimeter for Airborne Infrared Research (CORSAIR)